Report 4738

AN EVALUATION OF SPACE SHUTTLE STS-1 PAYLOAD BAY ACOUSTIC DATA AND COMPARISON WITH PREDICTIONS

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1. INTRODUCTION

During the first launch (STS-1) of the Space Shuttle orbiter vehicle, sound pressure levels were measured at several locations in the payload bay of the vehicle and on the exterior surface. The data were obtained in order to provide validation for prediction procedures for interior and exterior sound pressure levels and to determine, independently, the acoustic environment in the payload bay during actual launch conditions.

One of the prediction procedures under investigation is that developed by BBN as a means of estimating the acoustic environment surrounding payloads in the bay. The development of this prediction procedure is described in [1] and the resulting computer program "Payload Acoustic Environment for Shuttle" (PACES) is available from NASA Goddard Space Flight Center. During the development of the analytical model for the acoustic environment in the payload bay, several experimental validations were performed using model scale structures and, in one case, the first orbiter vehicle, OV-101. However, in no case was the exterior acoustic field a good representation of that likely to be encountered during an actual launch, nor was the test vehicle an accurate representation of a flight configuration. Consequently it is highly desirable to compare predictions obtained from PACES with actual launch data. This report provides such a comparison for STS-1.

The basic approach to be followed in the analysis is that outlined in [2], and the reader is referred to that document for details of the procedures. Unfortunately, data were not available for all the exterior microphone locations identified in [2], due to equipment malfunction or to the fact that microphones were not installed on the vehicle. Consequently, the data analysis procedure for the exterior sound levels was modified somewhat from that outlined in [2]. A similar approach was followed in an earlier report [3] concerned with results from the Flight Readiness Firing (FRF).

The data available for the analysis were provided by the NASA "30-Day Report" [4] and by subsequent additional data reduction performed by NASA at BBN's request. Bias error corrections were applied to the interior sound level data in order to obtain space-average values. In addition, corrections were also proposed to account for reflection effects at payload bay bulkheads and acoustic leaks through vents in the sidewalls of the bay. These latter two corrections are the result of rather crude assumptions and are thus tentative. Consequently it is not possible at this stage to draw definite conclusions regarding the accuracy of PACES. Rather, such conclusions are delayed pending the results from STS-2 where there are many more microphones in the payload bay.

This report first identifies (Section 2) microphone locations associated with the interior and exterior sound measurements, and then provides a general assessment of the data (Section 3). Section 4 and 5 then give a more detailed evaluation of the interior and exterior sound pressure levels, respectively. In the case of the interior levels, the objective is to obtain an unbiased estimate of the space-average values, whereas the analysis of exterior sound levels provides data input for the PACES computer program. Predictions of the payload bay sound pressure levels, obtained by use of PACES, are discussed in Section 6, and the potential effects of the open vents of the payload bay are described in Section 7. Conclusions arising from the evaluation are given in Section 8.

2. MICROPHONE LOCATIONS AND DATA ANALYSIS APPROACH

During STS-1 launch, sound pressure levels were measured in the payload bay of the orbiter vehicle, on the exterior of the vehicle and in the aft fuselage. Four microphones were located in the bay and their positions are shown in Figure 1. Three of the microphones (I1, I2, and I3) were located near large reflecting surfaces such as bulkheads or sidewall structure. The fourth microphone was attached to the DFI payload. Also one microphone, #692, (Microphone No. V08Y9692A) was mounted in the aft fuselage (Figure 2).

Several microphones were located on the fuselage and wing of the orbiter vehicle and data from twelve of these microphones were available for analysis. The twelve locations are identified in Figure 2. The number of exterior microphone locations providing useful information was less than anticipated in [2]. This is because it was found that several microphones were not installed and that some of the other microphones provided data which was suspected to be incorrect and, therefore, rejected from the analysis.

The data analysis for the four interior microphones is directed towards obtaining a space-average sound level within the payload bay. Since the microphones are few in number and their spatial distribution is biased, estimates have to be made of the appropriate bias corrections. The derivation of these bias corrections is discussed in [2] and need not be repeated here. Additional corrections to account for acoustic reflections at large surfaces are also derived in [2], but the validity of these reflection corrections has not yet been established. Thus, they should be considered only as preliminary.

Data from the exterior microphones and the microphone in the aft fuselage are to be used to construct, as well as possible, the

Microphone Locations

I.D.	X	Y	Z
I 1	576	4	423
I 2	863	-91	381
I 3	1307	11.5	400
I 4	1039	0	427

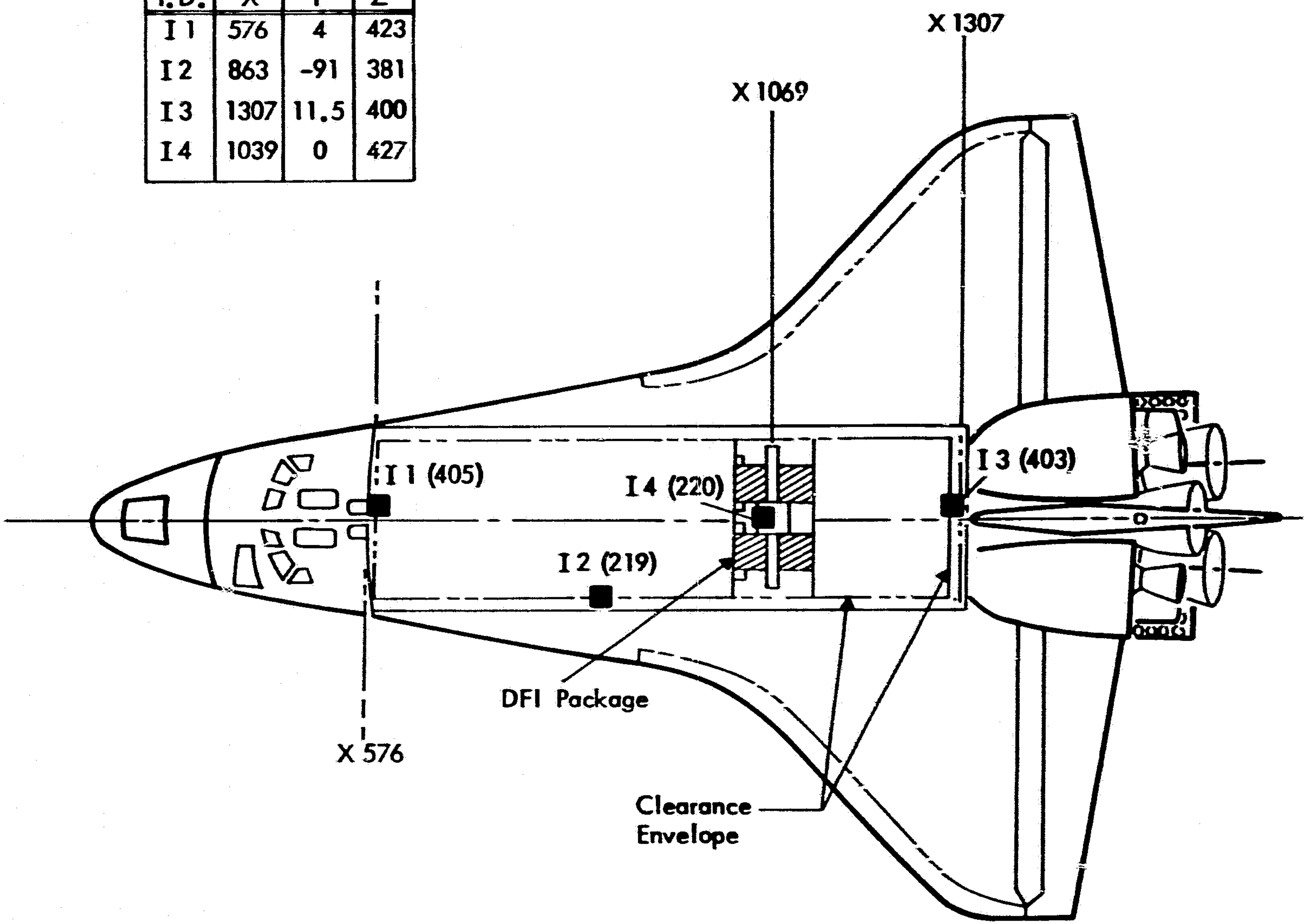

FIGURE 1. INTERNAL MICROPHONE LOCATIONS FOR STS-1

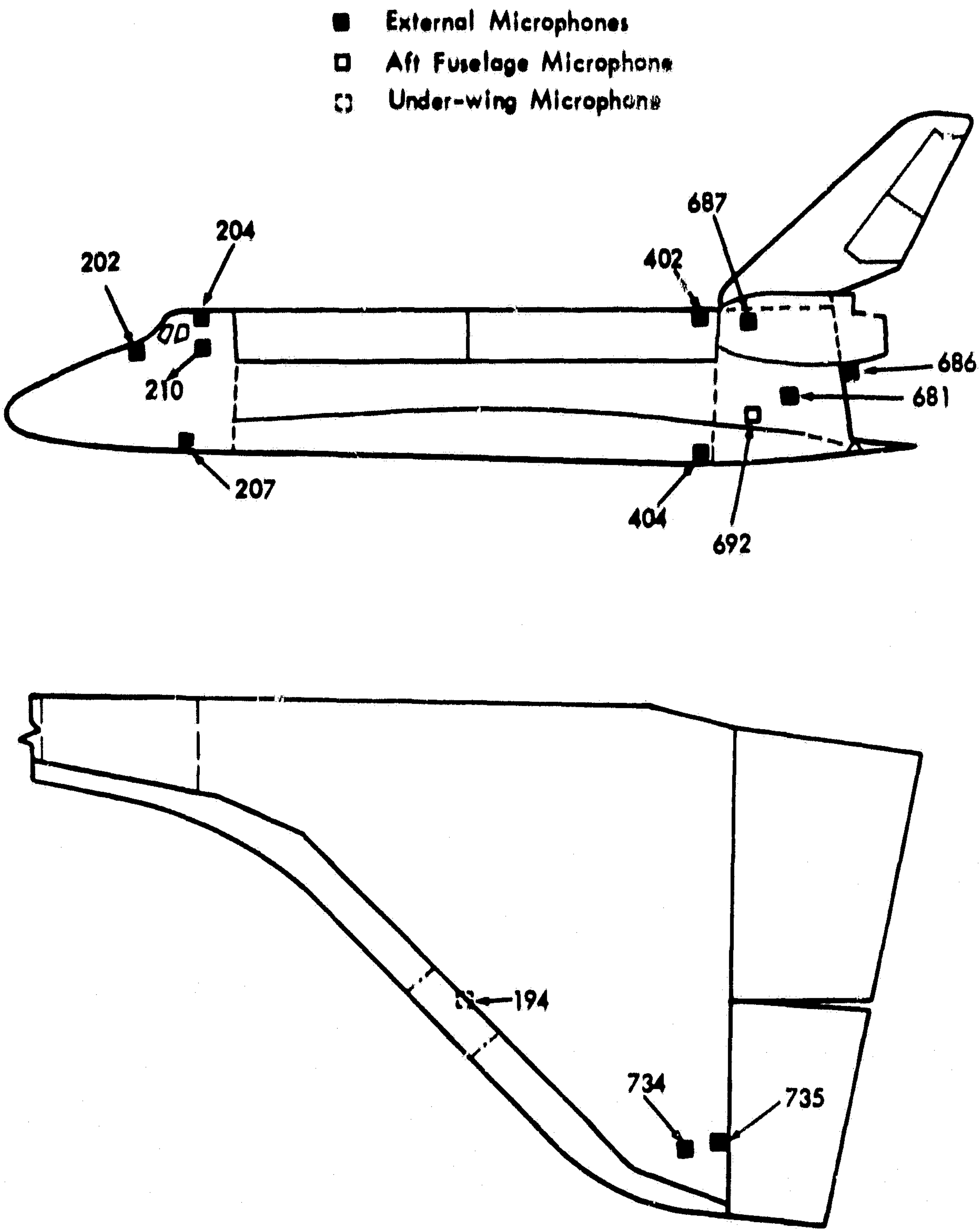

FIGURE 2. LOCATIONS OF MICROPHONES WHICH PROVIDED DATA ON EXTERIOR SOUND FIELD FOR STS-1

acoustic pressure field external to the payload bay. This pressure field has to be described in such a manner that the information can be used as data inputs to the PACES computer program, replacing the pressure levels which were derived on the basis of 6.4% model test and which form the current PACES data input [1]. It is apparent from an inspection of Figure 2 that the majority of the microphones are not located on the exterior surfaces of the payload bay and those that are on the mid-fuselage are only at the very aft end. Consequently methods have to be devised to obtain estimates of the space-average sound levels on the structural regions of interest. Discussion of this modeling of the exterior field is contained in Section 5.

3. GENERAL ASSESSMENT OF DATA

The acoustic data presented in the "30-day" report [4] and provided separately by NASA are generally of marginal quality. One exterior microphone on the forward end of the payload bay doors (Microphone No. VO8Y9401A) was inoperative and produced no useful data. A momentary loss of signal during lift-off was reported for two other microphones, the first exterior on the aft end of the payload bay doors (Microphone No. VO8Y9402A) and the second interior on the aft bulkhead (Microphone No. VO8Y9403A). In both cases, however, the duration of the loss-of-signal condition was short and easily deleted from the final computations of one-third octave band levels. Beyond this, the data from all four of the interior microphones display a signal-to-noise (S/N) ratio of less than 10 dB at frequencies above 2000 Hz. Finally, at frequencies below 100 Hz, the interior levels measured at the forward bulkhead are generally higher than the levels measured at other locations inside the payload bay, including the aft bulkhead. This is contrary to expectations, but there is no physical evidence at this time which challenges the validity of the forward bulkhead measurement.

The data were analyzed in a number of ways including rms values in one-third octave bands, expressed in dB referenced to 20 Pa. The one-third octave band levels were determined from the maximum value of running rms levels in each one-third octave band computed with an averaging time of 0.5 secs. over the time interval from T - 6 to T + 12 secs. (T = 0 is the time of the SRB ignition). The loss-of-signal anomalies discussed previously were omitted in the determination of the maximum levels during the time interval of interest.

4. EVALUATION OF INTERIOR DATA

The maximum one-third octave band levels measured during the lift-off phase (T - 6 to T + 12) by the four internal microphones are detailed in Table 1. Note that the levels at higher frequencies where the S/N ratio is less than 10 dB have been adjusted for background noise by

$$L = 10 \log \left[10^{L_r/10} - 10^{L_b/10} \right] \tag{1}$$

where L_r = sound presssure level as read in dB and L_b = sound pressure level of background noise in dB. The background noise levels were determined from measurements made at T + 120 seconds when both acoustic and aerodynamic excitations were minimal.

Also shown in Table 1 are the energy averages of the four interior microphone measurements, bias correction factors, space-average estimates, and 90% confidence limits for the true space-average levels. The energy averages in Table 1 are computed from

$$L_{ea} = 10 \log \left[\sum_{i=1}^{4} 10^{L_i/10} /4 \right] \tag{2}$$

where L_i is the sound pressure level in dB measured by the ith microphone. The bias correction factors in Table 1 account for the fact that the four available microphone measurements do not represent an unbiased sample of the payload bay acoustic levels. The derivation of these corrections is presented in [2]. The final corrected estimates of the space-average levels are given by

$$L_{sa} = L_{ea} + \Delta \tag{3}$$

where L_{ea} is defined in Eq. (2) and Δ is the bias correction factor.

Table 1. Measured Sound Pressure Levels in Payload Bay During STS-1 Lift-Off (Space-Average Value excludes Reflection Effects)

Freq. (Hz)	Measured Sound Pressure Levels, dB				Energy Average dB	Bias Correct. dB	Space Average dB	90% Conf.Limits	
	I1	I2	I3	I4				Lower, dB	Upper dB
12	120.0	112.0	118.8	111.0	117.1	1.0	118.1	-	121.1
16	123.0	119.2	117.0	120.1	120.4	-0.5	119.9	114.7	122.2
20	120.1	117.0	115.5	113.0	117.2	-0.5	116.7	109.5	119.2
25	119.2	117.0	114.0	114.6	116.7	1.0	117.7	112.9	119.9
31	119.2	118.5	112.0	113.0	116.8	2.5	119.3	110.8	121.9
40	125.1	120.1	112.0	115.2	120.7	2.0	122.7	-	126.6
50	126.3	121.0	114.0	117.3	122.0	2.0	124.0	-	127.7
63	129.7	123.0	115.0	119.3	124.9	1.5	126.4	-	130.6
80	127.0	127.2	122.0	121.1	125.2	1.0	126.2	119.9	128.6
100	125.8	125.5	124.5	122.4	124.7	0.0	124.7	122.8	126.1
125	125.7	128.0	124.0	120.7	125.4	0.0	125.4	119.3	127.8
160	126.0	125.0	124.5	121.0	124.5	-0.5	124.0	121.2	125.7
200	126.0	121.3	124.0	122.8	123.9	0.0	123.9	120.4	125.8
250	123.0	122.0	124.5	122.1	123.0	0.0	123.0	121.2	124.3
315	121.1	120.0	123.0	120.0	121.2	0.0	121.2	118.9	122.7
400	118.9	119.1	120.2	115.9	118.8	0.0	118.8	116.4	120.3
500	117.0	117.5	117.0	114.0	116.6	0.0	116.6	114.6	117.9
630	114.0	117.3	118.0	111.2*	115.9	0.0	115.9	110.5	118.2
800	113.5	115.1	113.2	109.4*	113.2	0.0	113.2	109.9	115.1
1000	113.0	115.0	110.0	108.0*	112.3	0.0	112.3	105.6	114.8
1250	112.0	115.0	106.7*	109.3*	111.8	0.0	111.8	100.6	114.7
1600	111.6	114.0	107.7*	110.6*	111.5	0.0	111.5	106.8	113.8
2000	112.0	111.4*	108.7*	109.2*	110.5	0.0	110.5	108.1	112.1
2500	110.6*	112.0*	109.6*	108.3*	110.3	0.0	110.3	108.0	111.9
3150	115.5	112.0*	112.7*	110.6*	113.1	0.0	113.1	109.0	115.1
4000	122.4	111.8*	119.4*	111.1*	118.6	0.0	118.6	-	122.1

* Values Adjusted Because of Poor Signal-to-Noise Ratio

The 90% confidence intervals for the true space-average levels are defined by

$$\text{upper 90\% limit} = 10 \log \left[\bar{\ell}_{ea} + \frac{t_{m;0.05}}{\sqrt{n}} s_\ell \right] + \Delta \qquad (4a)$$

$$\text{lower 90\% limit} = 10 \log \left[\bar{\ell}_{ea} - \frac{t_{m;0.05}}{\sqrt{n}} s_\ell \right] + \Delta \qquad (4b)$$

where $\bar{\ell}_{ea} = 10^{L_{ea}/10}$

$$s_\ell = \left[\frac{1}{n-1} \sum_{i=1}^{n} \left(\ell_i - \bar{\ell}_{ea} \right)^2 \right]^{\frac{1}{2}} .$$

$\ell_i = 10^{L_i/10}$

n = sample size = 4

$t_{m;0.05}$ = 0.05 percentage point of Student "t" variable with $m = n - 1 = 3$ degrees-of-freedom

Δ = bias correction factor.

The resulting space-average sound pressure level estimates and the 90% confidence intervals for the true space-average sound pressure levels are shown in Figure 3. Note that the lower 90% confidence limits are sometimes undefined. This occurs because the term $t_{m;0.05}\ s_\ell/\sqrt{n}$ in Eq. (4b) sometimes exceeds $\bar{\ell}_{ea}$, producing the logarithm of a negative number. The practical interpretation here is that the sample size of n = 4 is not sufficient relative to the scatter in the data to provide a meaningful estimate of the space-average levels, at least in terms of a lower bound. More accurate space-average level estimates are anticipated from STS-2 where the number of interior microphones will be n = 17.

Beyond the bias errors due to the small, unrepresentative sample size, the STS-1 payload bay measurements may also be biased by

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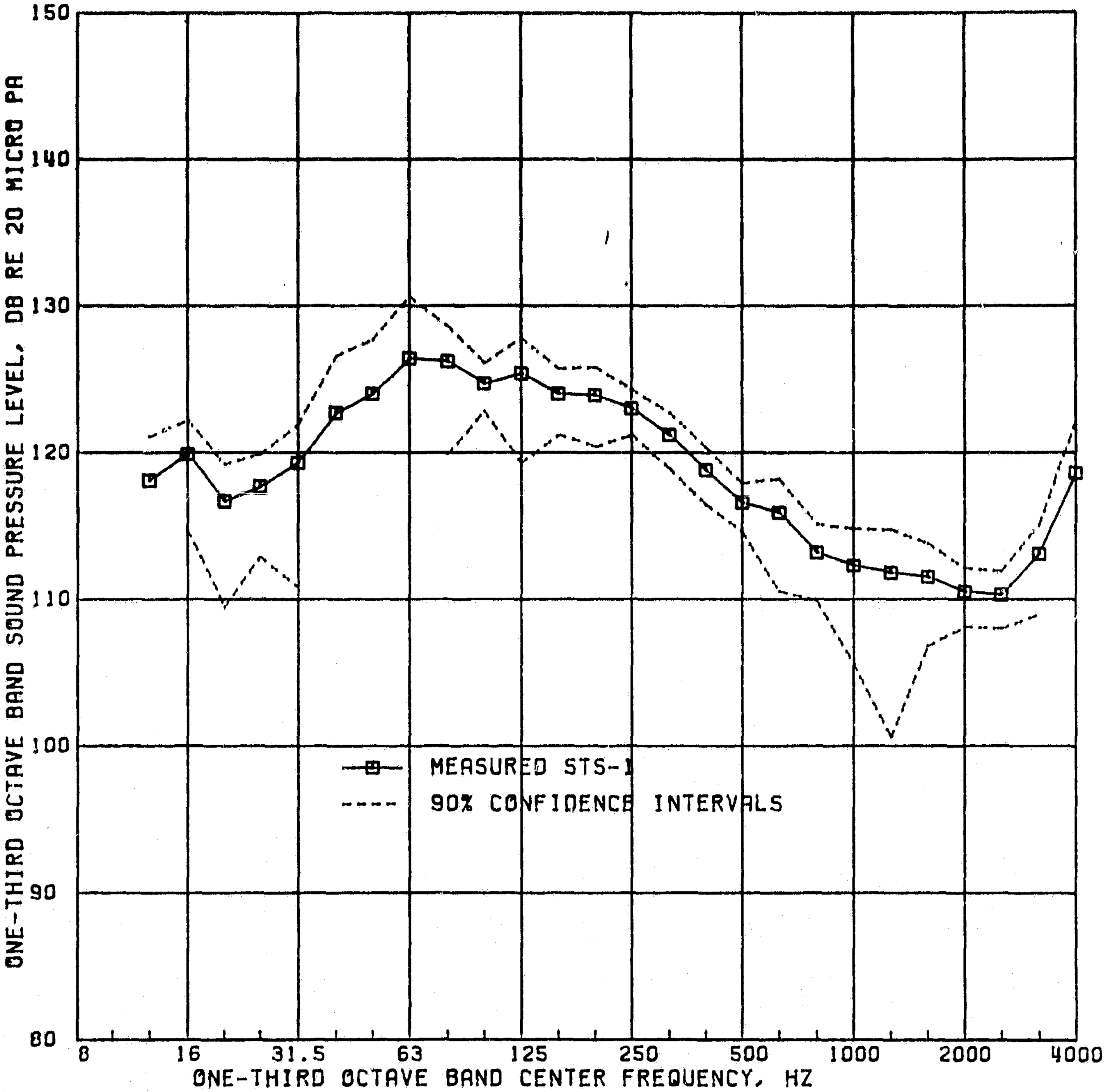

FIGURE 3. ESTIMATED SPACE-AVERAGE SOUND PRESSURE LEVELS IN PAYLOAD BAY DURING STS-1 LIFT-OFF (REFLECTION CORRECTIONS EXCLUDED)

the fact that three of the four bay microphones (I1 through I3) were mounted on large flat surfaces of the orbiter structure, namely, the forward bulkhead, left sidewall, and aft bulkhead, as illustrated in Figure 1. The possible bias errors due to the influence of surface reflections on these microphone measurements are derived in [2] and summarized in Table 2. The estimated payload bay space-average levels and 90% confidence limits with corrections for the reflection effects are listed in Table 3 and plotted in Figure 4. It should be noted that the derivation of the reflection correction factors in [2] is relatively crude and, hence, the results in Figure 4 include only a rough assessment of the reflection effects. Again, it is anticipated that STS-2 will provide more meaningful estimates of the payload bay space-average acoustic levels since most of the microphones in STS-2 are mounted on the corners of payload structures rather than on large flat surfaces.

Table 2. Reflection Correction Factors for STS-1 Sound Pressure Level Measurements

Frequency (Hz)	Reflection Correction Factor (dB)	Frequency (Hz)	Reflection Correction Factor (dB)
12.5	0	80	-2.0
16	-0.5	100	-2.5
20	-0.5	125	-2.0
25	-0.5	160	-2.0
31.5	-0.5	200	-2.0
40	-1.0	250	-1.0
50	-1.0	315 and above	0
63	-1.5		

Table 3. Measured Sound Pressure Levels in Payload Bay During STS-1 Lift-Off (Space-Average Value includes Reflection Effects)

Freq. (Hz)	Measured Sound Pressure Levels, dB				Energy Average dB	Bias Correct. dB	Space Average dB	90% Conf. Limits	
	I1	I2	I3	I4				Lower dB	Upper dB
12	120.0	112.0	118.8	111.0	117.1	1.0	118.1	-	121.1
16	123.0	119.2	117.0	120.1	120.4	-1.0	119.4	114.2	121.7
20	120.1	117.0	115.5	113.0	117.2	-1.0	116.2	109.0	118.7
25	119.2	117.0	114.0	114.6	116.7	0.5	117.2	112.4	119.4
31	119.2	118.5	112.0	113.0	116.8	2.0	118.8	110.3	121.4
40	125.1	120.1	112.0	115.2	120.7	1.0	121.7	-	125.6
50	126.3	121.0	114.0	117.3	122.0	1.0	123.0	-	126.7
63	129.7	123.0	115.0	119.3	124.9	0.0	124.9	-	129.1
80	127.0	127.2	122.0	121.1	125.2	-1.0	124.2	117.9	126.6
100	125.8	125.5	124.5	122.4	124.7	-2.5	122.2	120.3	123.6
125	125.7	128.0	124.0	120.7	125.4	-2.0	123.4	117.3	125.8
160	126.0	125.0	124.5	121.0	124.5	-2.5	122.0	119.2	123.7
200	126.0	121.3	124.0	122.8	123.9	-2.0	121.9	118.4	123.8
250	123.0	122.0	124.5	122.1	123.0	-1.0	122.0	120.2	123.3
315	121.1	120.0	123.0	120.0	121.2	0.0	121.2	118.9	122.7
400	118.9	119.1	120.2	115.9	118.8	0.0	118.8	116.4	120.3
500	117.0	117.5	117.0	114.0	116.6	0.0	116.6	114.6	117.9
630	114.0	117.3	118.0	111.2*	115.9	0.0	115.9	110.5	118.2
800	113.5	115.1	113.2	109.4*	113.2	0.0	113.2	109.9	115.1
1000	113.0	115.0	110.0	108.0*	112.3	0.0	112.3	105.6	114.8
1250	112.0	115.0	106.7*	109.3*	111.8	0.0	111.8	100.6	114.7
1600	111.6	114.0	107.7*	110.6*	111.5	0.0	111.5	106.8	113.8
2000	112.0	111.4*	108.7*	109.2*	110.5	0.0	110.5	108.1	112.1
2500	110.6*	112.0*	109.6*	108.3*	110.3	0.0	110.3	108.0	111.9
3150	115.5	112.0*	112.7*	110.6*	113.1	0.0	113.1	109.0	115.1
4000	122.4	111.8*	119.4*	111.1*	118.6	0.0	118.6	-	122.1

* Values Adjusted Because of Poor Signal-to-Noise Ratio

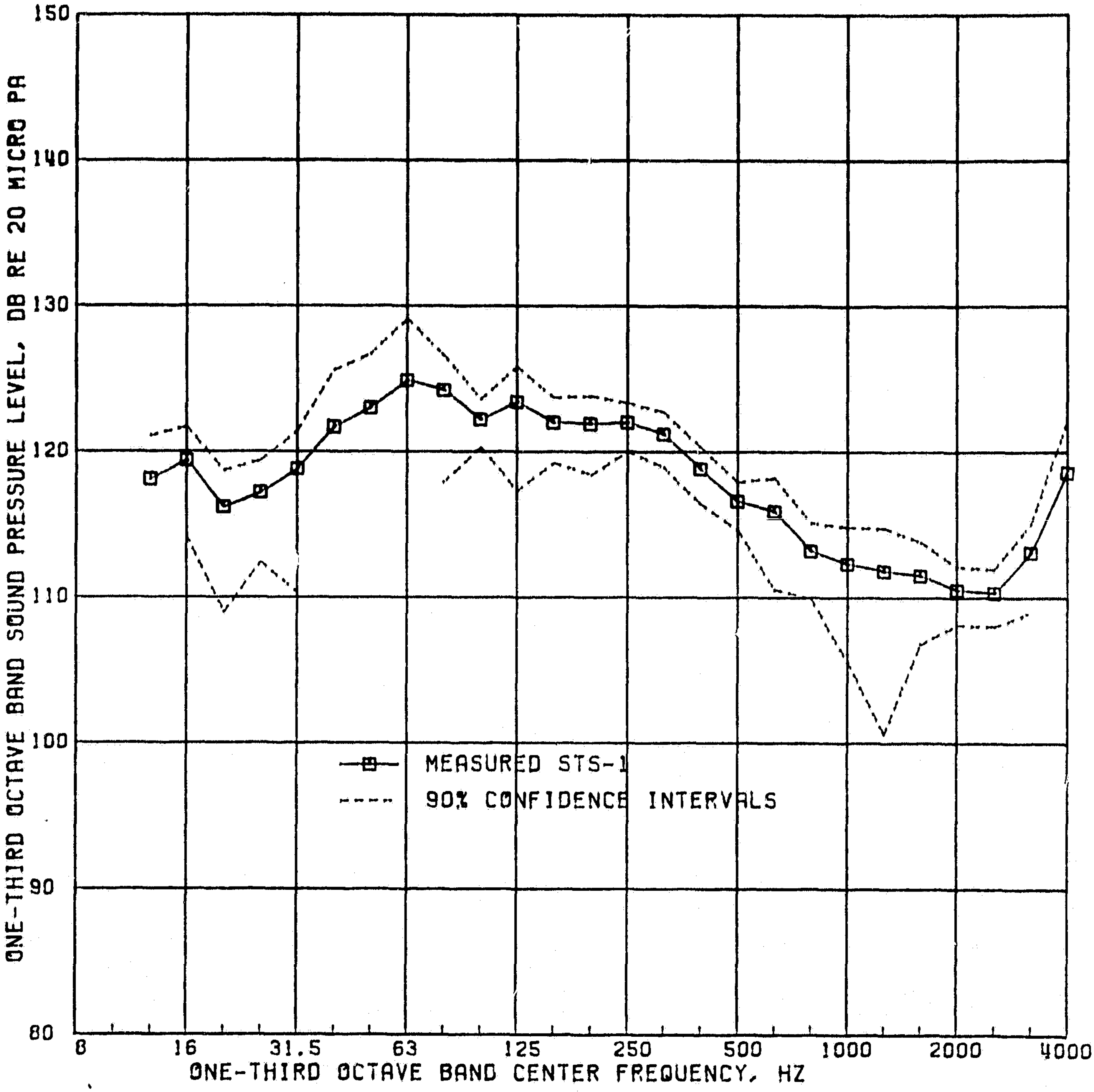

FIGURE 4. ESTIMATED SPACE-AVERAGE SOUND PRESSURE LEVELS IN PAYLOAD BAY DURING STS-1 LIFT-OFF (REFLECTION CORRECTIONS INCLUDED)

5. EVALUATION OF EXTERIOR DATA

The objective of the evaluation of the measured exterior sound levels is to generate data input information for use in the computation of payload bay sound levels using the PACES computer program. In [1], exterior sound levels are estimated for launch conditions on the basis of data from 6.4% scale model tests performed by NASA. The results from STS-1 provide the first information regarding the actual sound levels at launch. Consequently there is a need to revise the data input package for PACES to make it consistent with launch data.

For computational purposes, the exterior structure of the payload bay of the orbiter vehicle is modeled as six regions in PACES. These regions are:-

(1) Payload bay doors	Sta 582 to 1307
(2) Bottom structure (forward region)	Sta 582 to 1191
(3) Bottom structure (aft region)	Sta 1191 to 1307
(4) Sidewall (forward region)	Sta 582 to 1040
(5) Sidewall (aft region)	Sta 1040 to 1307
(6) Aft bulkhead	Sta 1307

(It is assumed that there is no acoustic power flow through the forward bulkhead of the payload bay). The analytical model for PACES requires that a space-average sound pressure level spectrum, in one-third octave frequency bands, be provided for each region. These spectra are used as data inputs to the computer program. The evaluation of the STS-1 exterior sound levels has to be performed in order to determine estimates for these six spectra. The approaches used in determining these spectra are described briefly in the following discussion.

5.1 Estimation of Space-Average Sound Levels

Payload Bay Door:

Data are available for microphone locations 402 (Microphone No. V08Y9402A at X = 1300) at the aft end of the payload bay door and 204 (Microphone No. V08Y9204A at X = 520) on the top of the forward fuselage just forward of the payload bay. A comparison of the one-third octave band levels shows that the values are almost the same for the two locations, as is shown in Figure 5. Thus, space-average sound levels were computed by taking the energy average of the sound levels at the two locations.

This approach makes two assumptions. Firstly, it is assumed that the similarity of the sound levels at locations 204 and 402 implies that there is no significant variation in sound level along the length of the door. Secondly it is assumed that the sound levels along the door centerline are typical of the levels in the circumferential direction. The only information regarding the circumferential distribution of sound levels on the door is provided by location 210 (Microphone No. V08Y9210A at X = 540, Z = 420). This location is on the side of the forward fuselage, at approximately the same longitudinal station as location 204. The sound levels at 210 are similar to those at 204, for frequencies below 100 Hz, but at higher frequencies the sound levels are 2 to 3 dB higher than those at 204. However if data for locations 204 and 210 were energy-averaged to obtain an estimate of the sound levels at the forward end of the door, the net effect on the door space-average sound level would be less than 1 dB. Furthermore, the coordinate for location 210 corresponds roughly to the hinge line of the payload bay door and to a region of the door which is highly-curved and, thus, stiff. Consequently the slightly higher sound levels measured at location 210 will probably have a negligible effect on the acoustic power transmitted through the door, and the data were not

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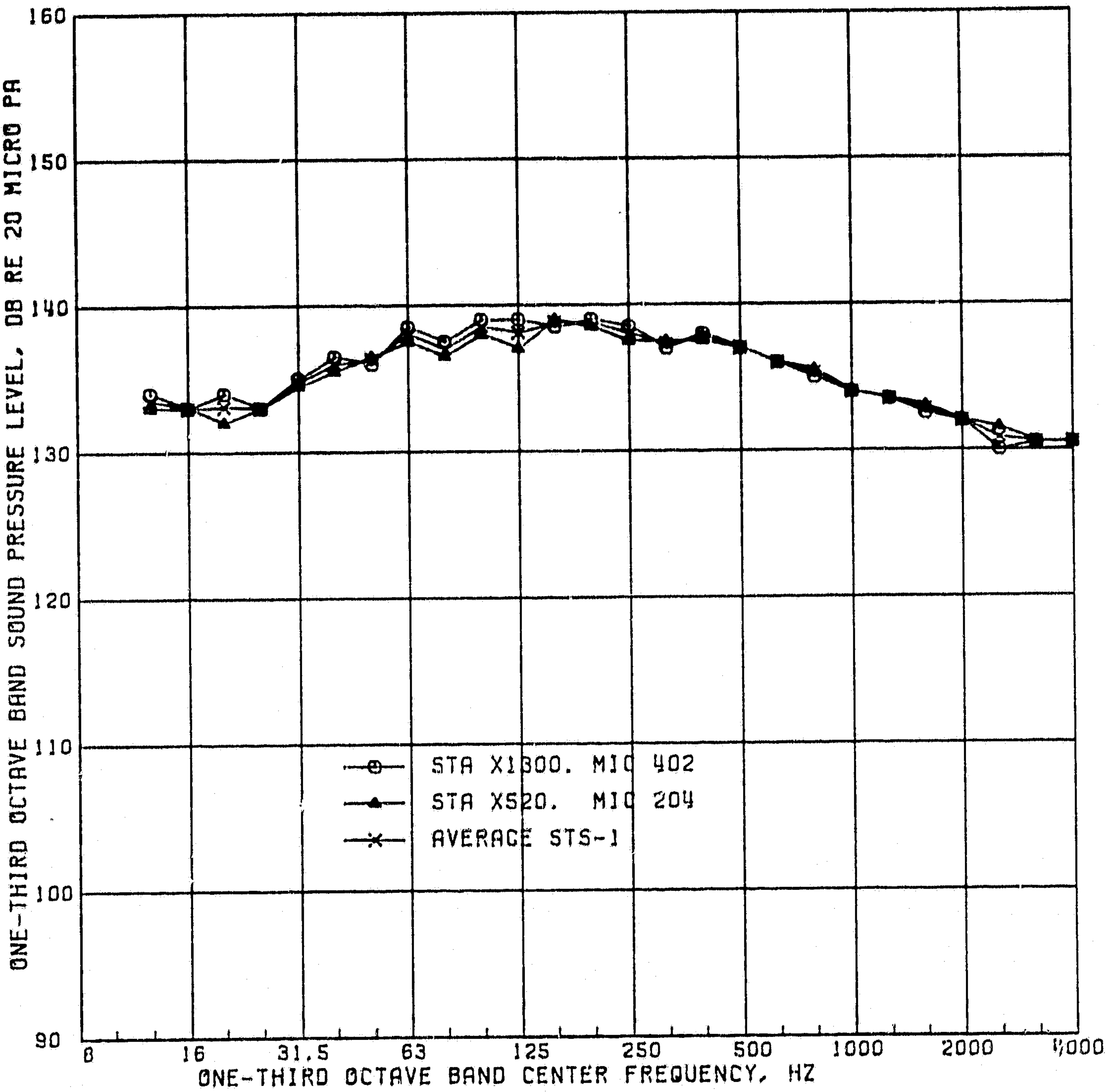

FIGURE 5. SOUND LEVELS ON PAYLOAD BAY DOOR (STS-1)

included in the computation of the space-average sound levels on the door.

When the space-average sound level spectrum computed for STS-1 is compared with that computed for OV-102 [1] on the basis of NASA 6.4% model tests, it is found that the STS-1 levels are generally 4 to 6 dB lower, as shown in Figure 6.

Sidewall:

Data are available for microphone locations 681 (Microphone No. V08Y9681A at X = 1420) on the aft fuselage and 210 (Microphone No. V0849210A at X = 540) on the forward fuselage. There was no microphone location on the sidewall of the mid-fuselage. Consequently some method has to be devised to interpolate between the two measurement locations.

As can be seen in Figure 7, the sound levels at the two locations differed by up to 10 dB, in contrast to the sound levels at the forward and aft ends of the door where the levels were almost equal. Furthermore, it is required to obtain space-average sound levels for two different areas on the sidewall. It is thus not possible simply to take the energy average of the sound levels at the two measurement locations. Two alternative approaches were tried. In the first approach it was assumed that the mean square pressure varied inversely with the square of the distance from the source (i.e. free field of a point source) and in the second method the mean square pressure was assumed to vary inversely with distance (i.e. a line source). The inverse square law was finally adopted because the effective source locations were more acceptable from physical considerations. At low frequencies the effective source locations were 100 to 200 feet aft of the orbiter vehicle and at high frequencies, 25 to 50 feet.

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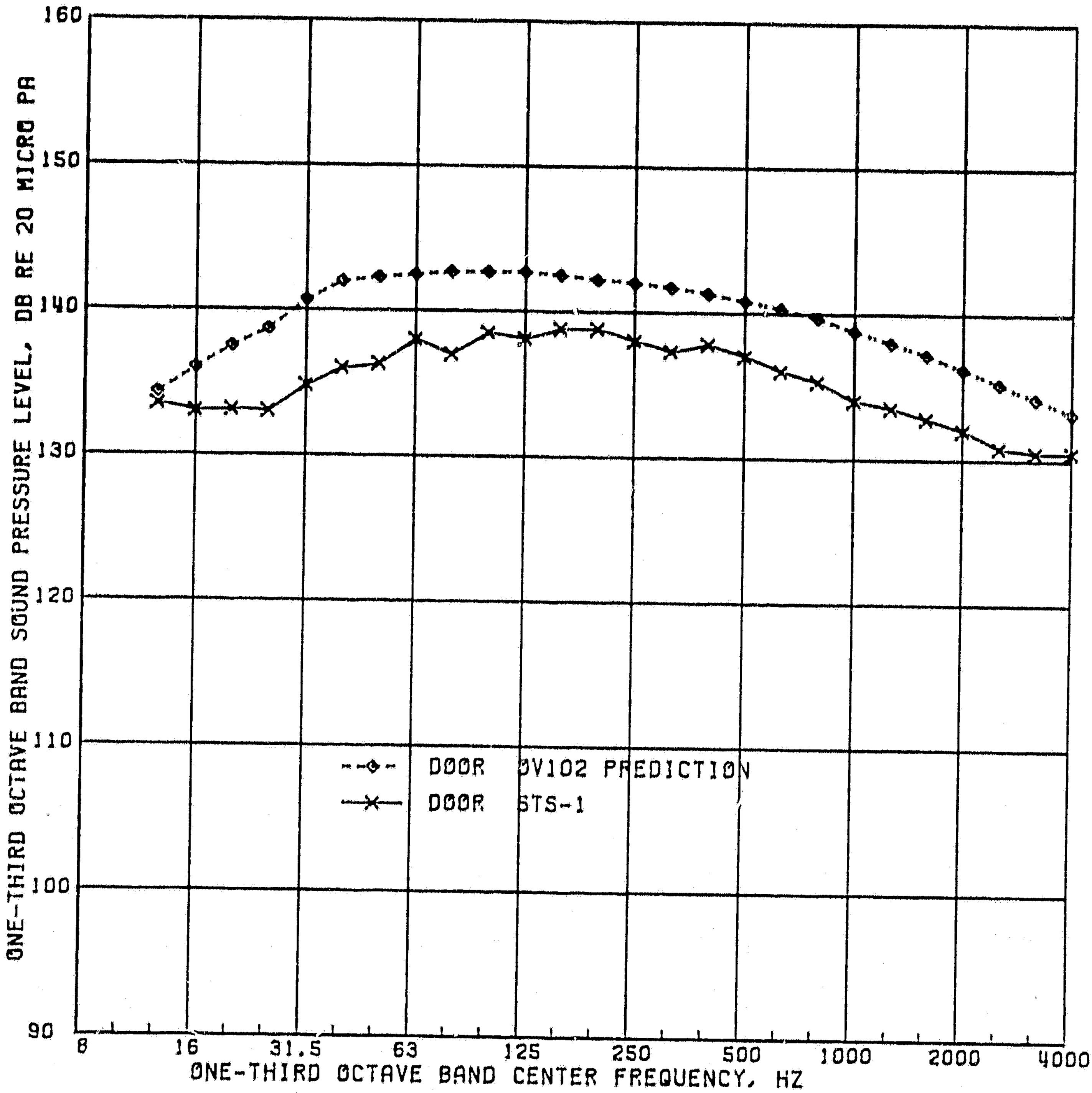

FIGURE 6. COMPARISON OF SPACE-AVERAGE SOUND LEVELS IN PAYLOAD BAY DOOR (STS-1 AND OV102 PREDICTION)

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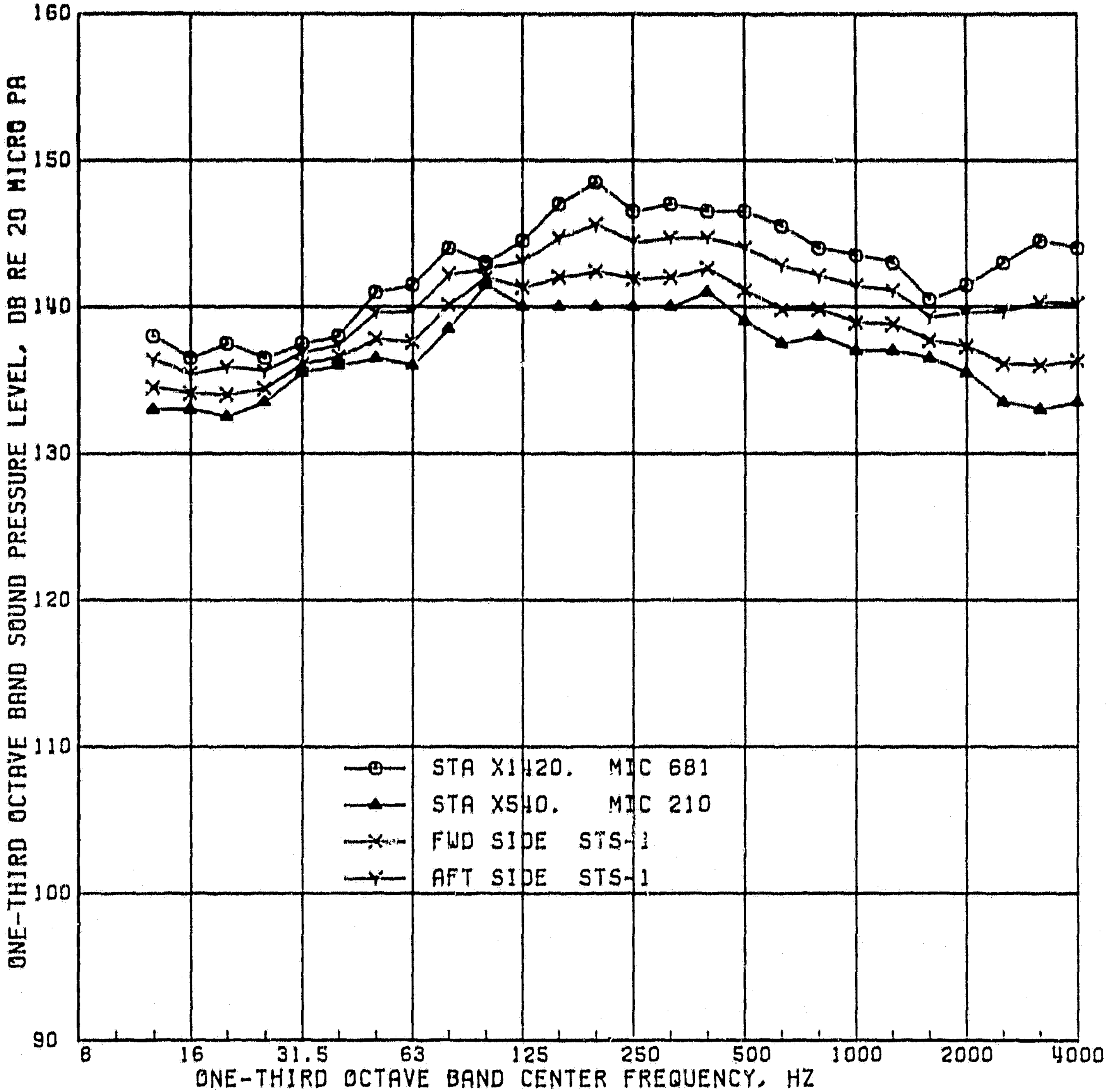

FIGURE 7. SOUND LEVELS ON MID-FUSELAGE SIDEWALL (STS-1)

Applying the inverse square law to the measured sound levels at X = 540 and 1420, an effective source location was determined at each one-third octave band center frequency. The inverse square law was then used to estimate sound levels at the forward (X = 582) and aft (X = 1307) ends of the sidewall, and at X = 1040, the boundary between the forward and aft regions of the sidewall. Finally, the sound levels at X = 582 and X = 1040 were averaged on an energy basis to obtain space-average levels for the forward region, and a similar process was applied to sound levels at X = 1040 and 1370 for the aft region. It was found that the resulting sound levels were generally within 0.5 dB of those estimated for the center locations of the fore and aft regions, using the inverse square law.

The estimated space-average sound levels for the forward and aft regions of the sidewall are plotted in Figure 7, and the levels are compared in Figure 8 with corresponding spectra predicted for OV-102 [1] on the basis of NASA 6.4% scale model tests. In this case it is found that the OV-102 predictions and the STS-1 data are similar in level, although the STS-1 data generally show a larger difference between the two regions.

The assumptions implicit in the estimation of space-average sound levels on the sidewall for STS-1 are the same as those for the door. These assumptions are (a) that the sound level varies monotonically in the longitudinal direction and (b) the sound level is essentially constant in the lateral direction. The same assumptions will also be adopted for the bottom structure.

Bottom Structure:

Data are available for microphone locations 404 (Microphone No. V08494O4A at X = 1300) on the aft region of the mid-fuselage bottom structure, and 207 (Microphone No. V0849207A at X = 500) on the bottom structure of the forward fuselage. No microphone

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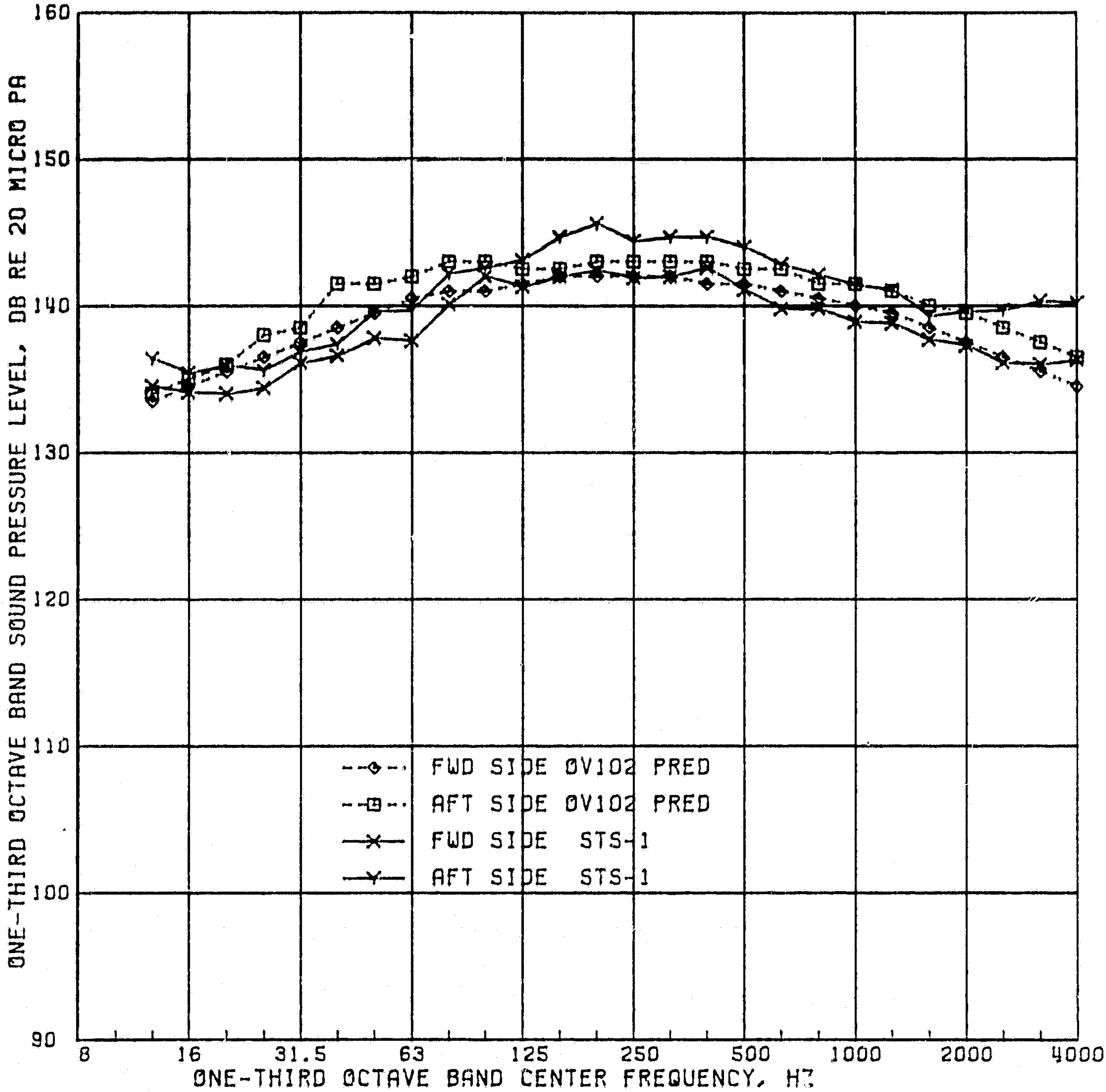

FIGURE 8. COMPARISON OF SPACE-AVERAGE SOUND LEVELS ON MID-FUSELAGE SIDEWALL (STS-1 AND OV102 PREDICTION)

was located on the forward region of the mid-fuselage bottom structure. Consequently it was again necessary to apply an interpolation procedure, and, for consistency, the inverse square law adopted for the sidewall was again used.

Sound levels measured at locations 404 and 207 are shown in Figure 9, where it is seen that the differences between the forward and aft locations are much smaller than is the case for the sidewall (Figure 7). Thus the precise nature of the interpolation procedure is less critical with regard to the accuracy of the estimates. Figure 9 also contains the estimated space-average sound levels for the forward and aft regions of the mid-fuselage bottom structure. For the aft region the space-average levels are very close to those measured at location 404, as is to be expected since the aft region extends for only a small distance in the longitudinal direction.

When the estimated space-average sound levels for STS-1 are compared with corresponding values predicted for OV-102 [1] on the basis of NASA 6.4% scale model data, a marked difference can be observed (Figure 10). This is particularly true for the aft region where the OV-102 model predicted an acoustic "hot-spot". No such effect is observed for STS-1 and the resulting space-average sound levels are 6 to 12 dB lower than for OV-102. The STS-1 sound levels for the forward region are also lower than those predicted for OV-102, although the differences are somewhat smaller (2 to 4 dB).

Bulkhead:

Sound levels in the aft fuselage were measured at only one location, 692 (Microphone No. V0849692A), shown in Figure 2. In the absence of any other information, it is therefore assumed that the sound levels measured at that location are representative of the space-average values on the aft bulkhead of the payload bay.

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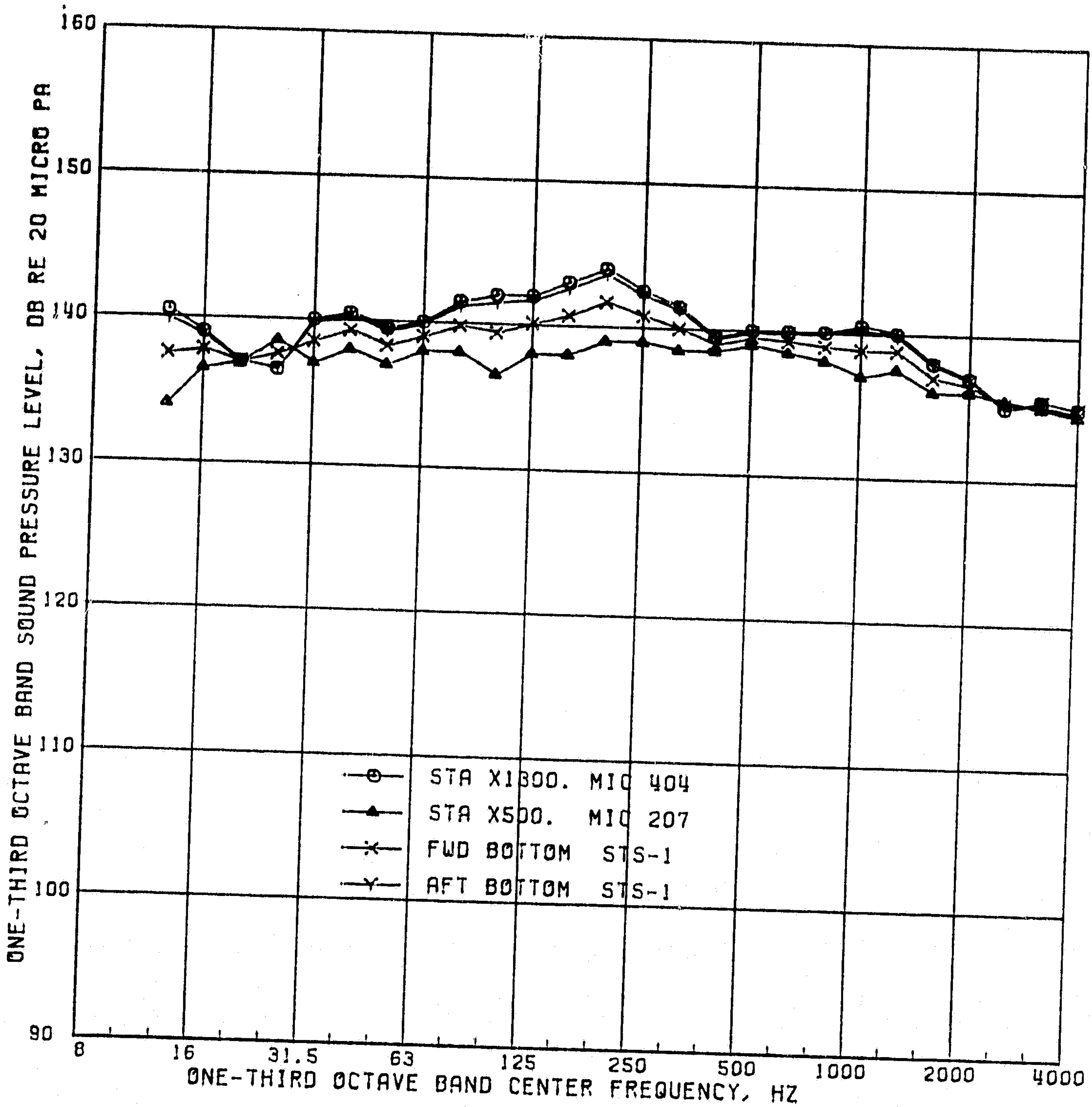

FIGURE 9. SOUND LEVELS ON MID-FUSELAGE BOTTOM STRUCTURE (STS-1)

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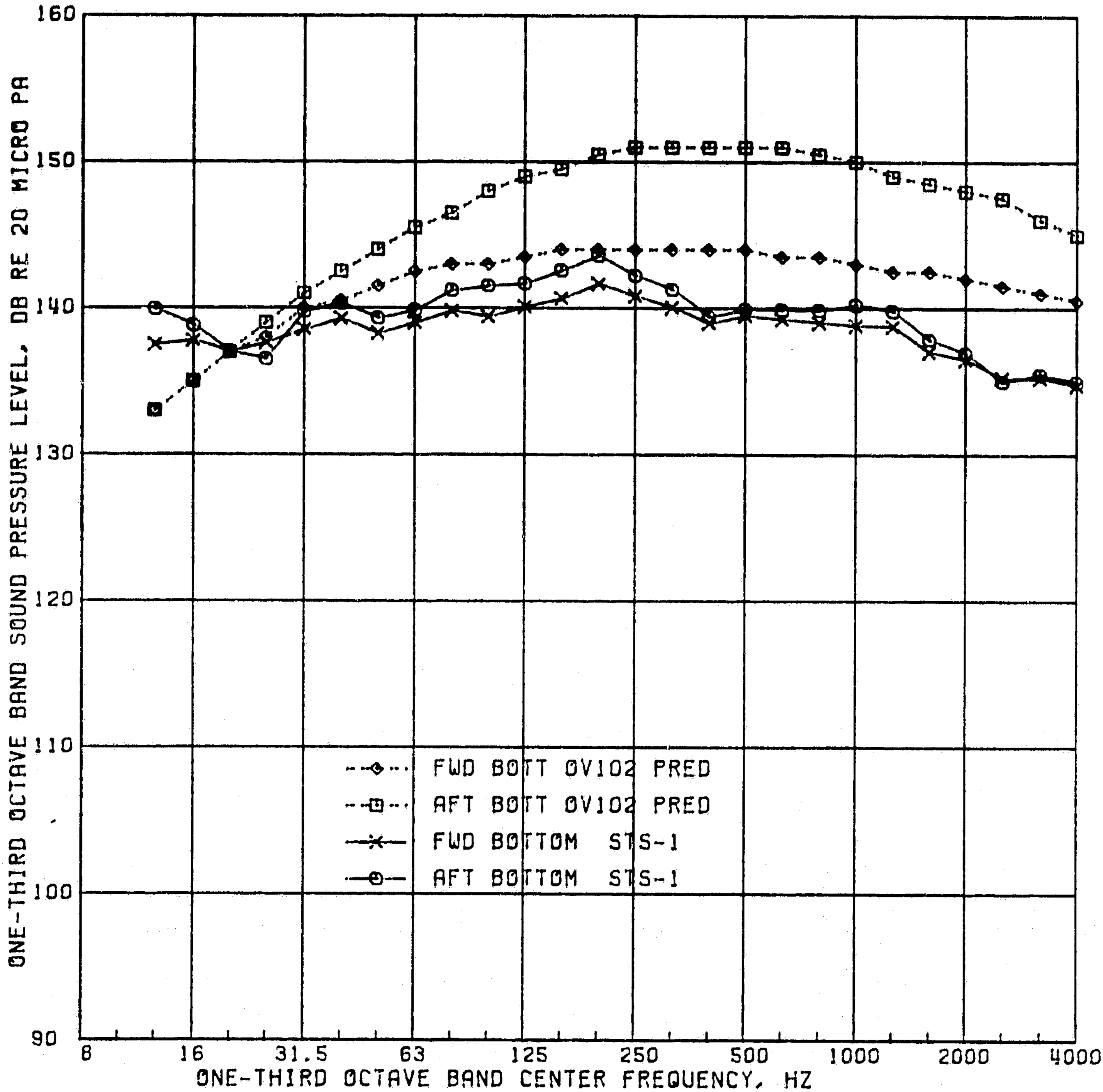

FIGURE 10. COMPARISON OF SPACE-AVERAGE SOUND LEVELS ON MID-FUSELAGE BOTTOM STRUCTURE (STS-1 AND OV102 PREDICTION)

The sound pressure level spectrum measured at location 692 is shown in Figure 11 where it is compared with the spectrum assumed for OV-102 [1]. It is seen that the STS-1 spectrum is much more irregular in shape than that assumed for OV-102, and the levels are, at many frequencies, 10 to 20 dB lower.

5.2 Data Input for PACES

The space-average sound levels calculated for the six structural regions bounding the Space Shuttle payload bay are required as data input for the PACES computer program in order to calculate interior sound levels for STS-1 lift-off. The six one-third octave band spectra, contained in Figures 5 through 11, are collected together in Figure 12 and tabulated in Table 4. For STS-1, these spectra directly replace those predicted for OV-102 and shown in Figure 41 of [5].

It should be recognized that the space-average levels in Figure 12 are based on sparse data and represent only the conditions present at the STS-1 launch. Data from subsequent launches are required to establish some statistical confidence in the data. The question of data accuracy is addressed in Section 6 by means of a brief sensitivity study which considers changes of ± 3 dB in the exterior space-average sound levels and the subsequent effects on the calculated interior sound levels.

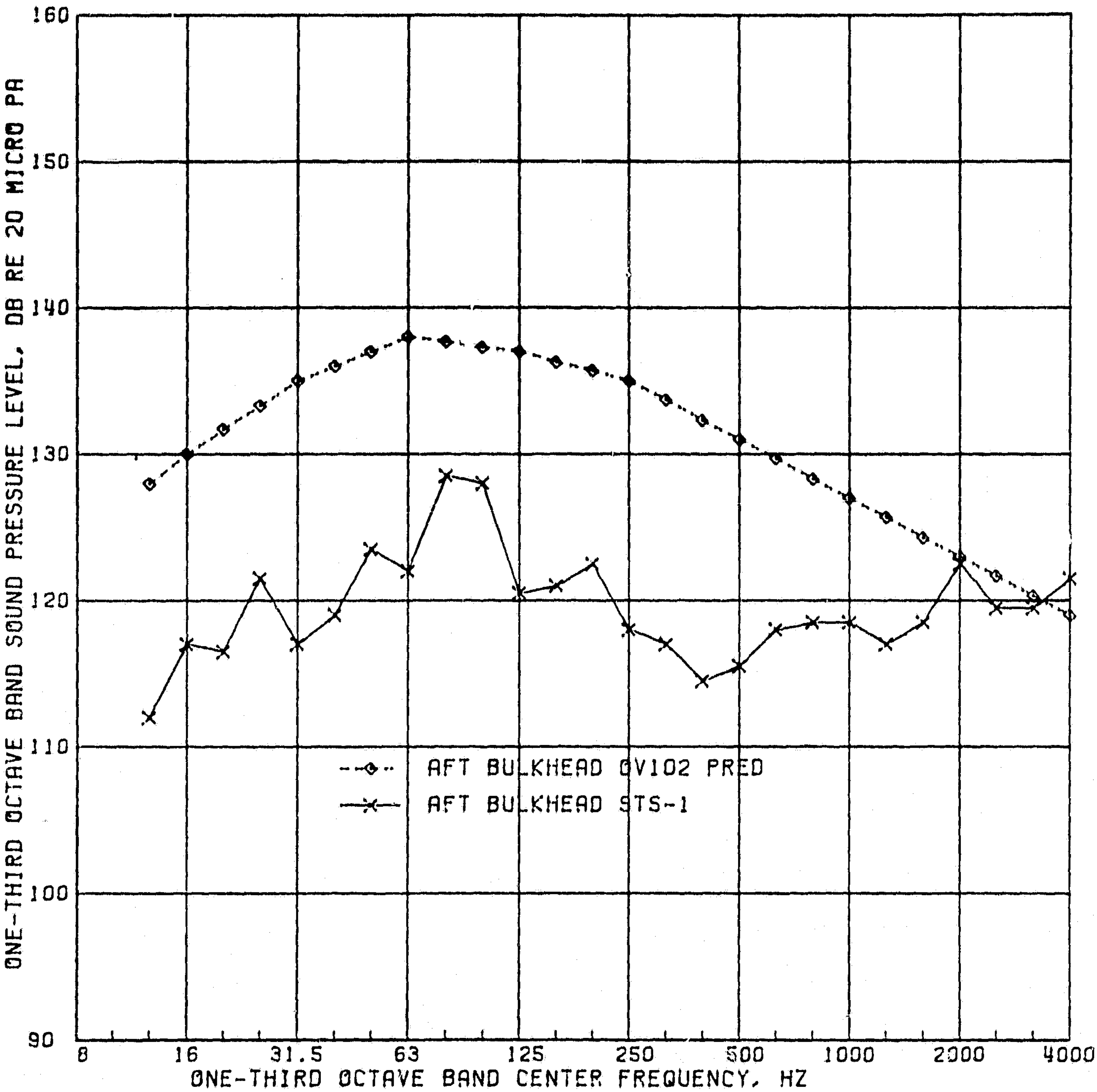

FIGURE 11. COMPARISON OF SPACE-AVERAGE SOUND LEVELS ON PAYLOAD BAY AFT BULKHEAD (STS-1 AND OV102 PREDICTION)

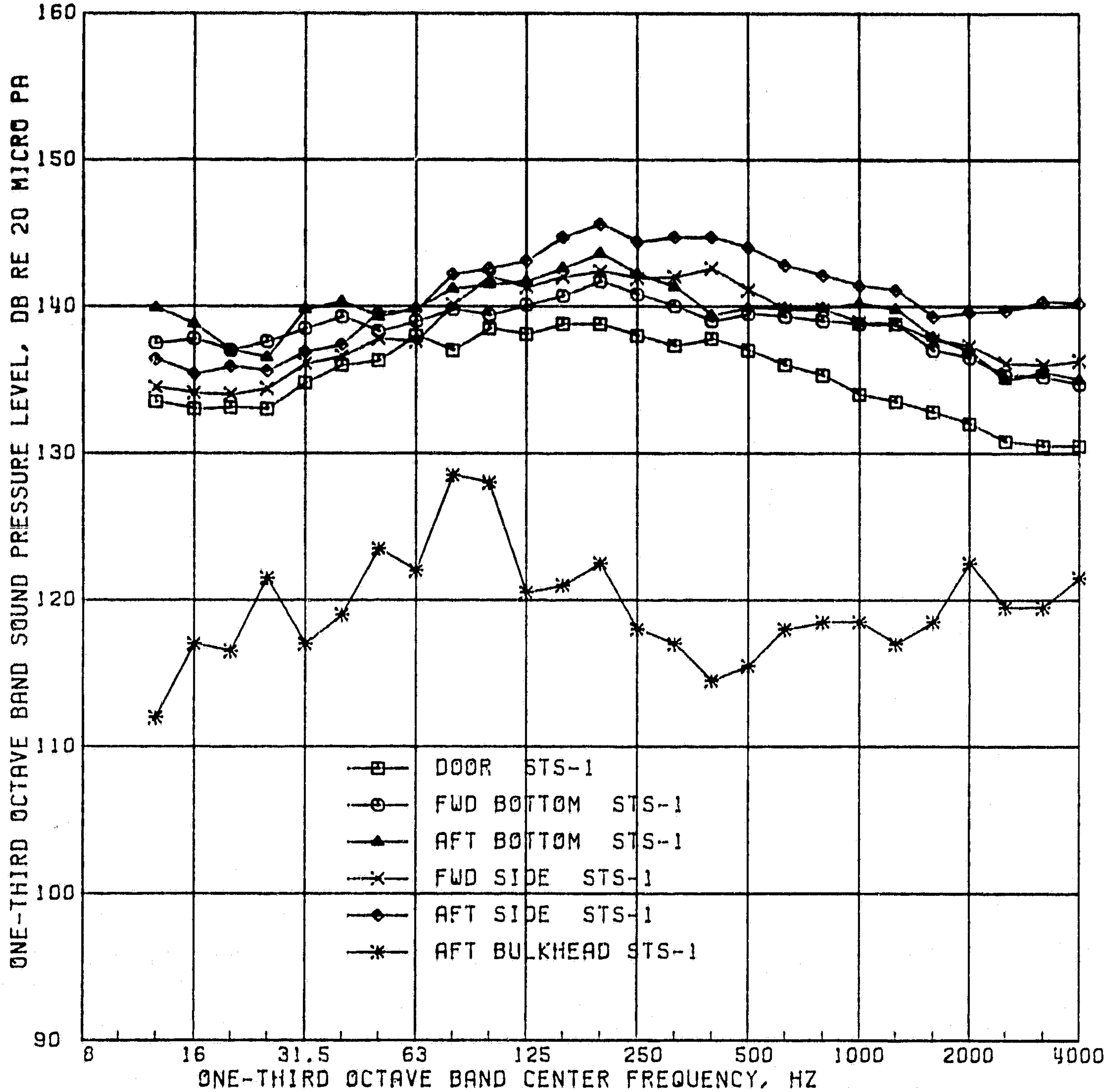

FIGURE 12. SPACE-AVERAGE SOUND LEVELS FOR EXTERIOR OF PAYLOAD BAY ESTIMATED FROM STS-1 DATA

Table 4. Exterior Space-Average Sound Pressure Levels for STS-1 (dB re 20 μPa)

FREQUENCY Hz	DOOR	BOTTOM STA 582 -1191	BOTTOM STA 1191 -1307	SIDEWALL STA 582 -1040	SIDEWALL STA 1040 -1307	AFT BULKHEAD
12.5	133.5	137.5	139.9	134.5	136.4	112.0
16	133.0	137.8	138.8	134.1	135.4	117.0
20	133.1	137.0	137.0	134.0	135.9	116.5
25	133.0	137.6	136.5	134.4	135.6	121.5
31.5	134.8	138.5	139.8	136.1	136.9	117.0
40	136.0	139.3	140.3	136.6	137.4	119.0
50	136.3	138.3	139.3	137.8	139.6	123.5
63	138.0	139.0	139.9	137.6	139.7	122.0
80	137.0	139.8	141.2	140.1	142.2	128.5
100	138.5	139.4	141.5	142.0	142.6	128.0
125	138.1	140.1	141.7	141.3	143.1	120.5
160	138.8	140.7	142.6	142.0	144.7	121.0
200	138.8	141.7	143.6	142.4	145.6	122.5
250	138.0	140.8	142.2	141.9	144.4	118.0
315	137.3	140.0	141.3	142.0	144.7	117.0
400	137.8	139.0	139.4	142.6	144.7	114.5
500	137.0	139.5	139.9	141.1	144.0	115.5
630	136.0	139.3	139.9	139.8	142.8	118.0
800	135.3	139.0	139.9	139.8	142.1	118.5
1000	134.0	138.8	140.2	138.9	141.4	118.5
1250	133.5	138.8	139.8	138.8	141.1	117.0
1600	132.8	137.0	137.9	137.7	139.3	118.5
2000	132.0	136.5	136.9	137.3	139.6	122.5
2500	130.8	135.3	135.0	136.1	139.7	119.5
3150	130.5	135.2	135.5	136.0	140.3	119.5
4000	130.5	134.7	135.0	136.3	140.2	121.5

6.0 PACES CALCULATIONS

6.1 Interior Space-Average Sound Levels

The STS-1 space-average exterior sound levels plotted in Figure 12 have been used as input data to the PACES computer program in order to predict space-average sound levels in the payload bay at lift-off. Two calculations have been performed, one of which assumes that there was no TCS material on the forward and aft bulkheads of the payload bay (as was assumed in [5]), and the other assumes that TCS is present on the bulkheads. This latter case was introduced because information received recently by BBN indicates that TCS is present on the orbiter vehicle bulkheads.

In order to account for the presence of the TCS on the bulkheads the acoustic absorption coefficients for the bulkheads are assumed to be the same as those for the forward sidewall (Table 6 of [5]). The revised table of absorption coefficients for the payload bay is shown in Table 5.

The calculated space-average interior sound levels are shown in Figure 13, where it can be seen that the effect of the TCS on the bulkheads is negligible at frequencies below 400 Hz, and even at higher frequencies, the differences in sound level are less than 1 dB. Excluding the effects of TCS changes, predicted sound levels for STS-1 are 3 to 6 dB lower than those predicted earlier [5] for OV-102. The differences are due entirely to the lower sound levels on the exterior of the payload bay.

6.2 Comparison with Measured Data

The predicted interior sound levels can be compared with the estimated space-average levels based on STS-1 measurements shown in Figures 3 and 4. The comparisons are shown in Figures 14

Table 5. Estimated Absorption Coefficients for Payload Bay

Frequency (Hz)	Door	Bulkhead	Sidewall & Bottom (Base)	Sidewall with TCS STA582-919	Sidewall with TCS STA919-1307	Sidewall with TCS Average	Bottom with TCS STA582-919	Bottom with TCS STA919-1307	Bottom with TCS Average	TCS Beneath	Payload
12.5	0.100	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.175
16		0.043	0.040	0.043	0.065	0.054	0.043	0.065	0.054	0.065	
20		0.045	0.040	0.045	0.090	0.068	0.045	0.090	0.068	0.090	
25		0.048	0.040	0.048	0.114	0.081	0.048	0.114	0.081	0.115	
31.5		0.050	0.040	0.050	0.140	0.095	0.050	0.140	0.095	0.140	
40		0.055	0.040	0.055	0.140	0.098	0.060	0.140	0.100	0.140	
50		0.060	0.040	0.060	0.145	0.103	0.065	0.145	0.105	0.145	
63		0.065	0.040	0.065	0.150	0.108	0.075	0.155	0.115	0.155	
80		0.075	0.050	0.075	0.165	0.120	0.095	0.170	0.133	0.170	
100		0.085		0.085	0.180	0.133	0.110	0.195	0.153	0.205	
125		0.100		0.100	0.200	0.150	0.125	0.230	0.178	0.260	
160		0.105		0.105	0.240	0.173	0.140	0.280	0.210	0.360	
200		0.115		0.115	0.280	0.198	0.165	0.375	0.270	0.500	
250		0.125		0.125	0.370	0.248	0.220	0.480	0.350	0.570	
315		0.210		0.210	0.460	0.335	0.310	0.540	0.425	0.605	
400		0.305		0.305	0.505	0.405	0.415	0.565	0.490	0.615	
500		0.400		0.400	0.525	0.463	0.480	0.570	0.525	0.615	
630		0.400		0.400	0.530	0.465	0.505	0.570	0.538	0.595	
800		0.400		0.400	0.530	0.465	0.520	0.570	0.545	0.570	
1000		0.400		0.400	0.520	0.460	0.530	0.565	0.548	0.550	
1250		0.400		0.400	0.510	0.455	0.535	0.560	0.458	0.530	
1600		0.400		0.400	0.505	0.453	0.535	0.550	0.543	0.510	
2000		0.400		0.400	0.490	0.445	0.535	0.540	0.538	0.500	
2500		0.395		0.395	0.470	0.433	0.525	0.530	0.525	0.490	
3150		0.390		0.390	0.455	0.423	0.520	0.520	0.520	0.480	
4000		0.390		0.390	0.430	0.410	0.510	0.510	0.510	0.470	

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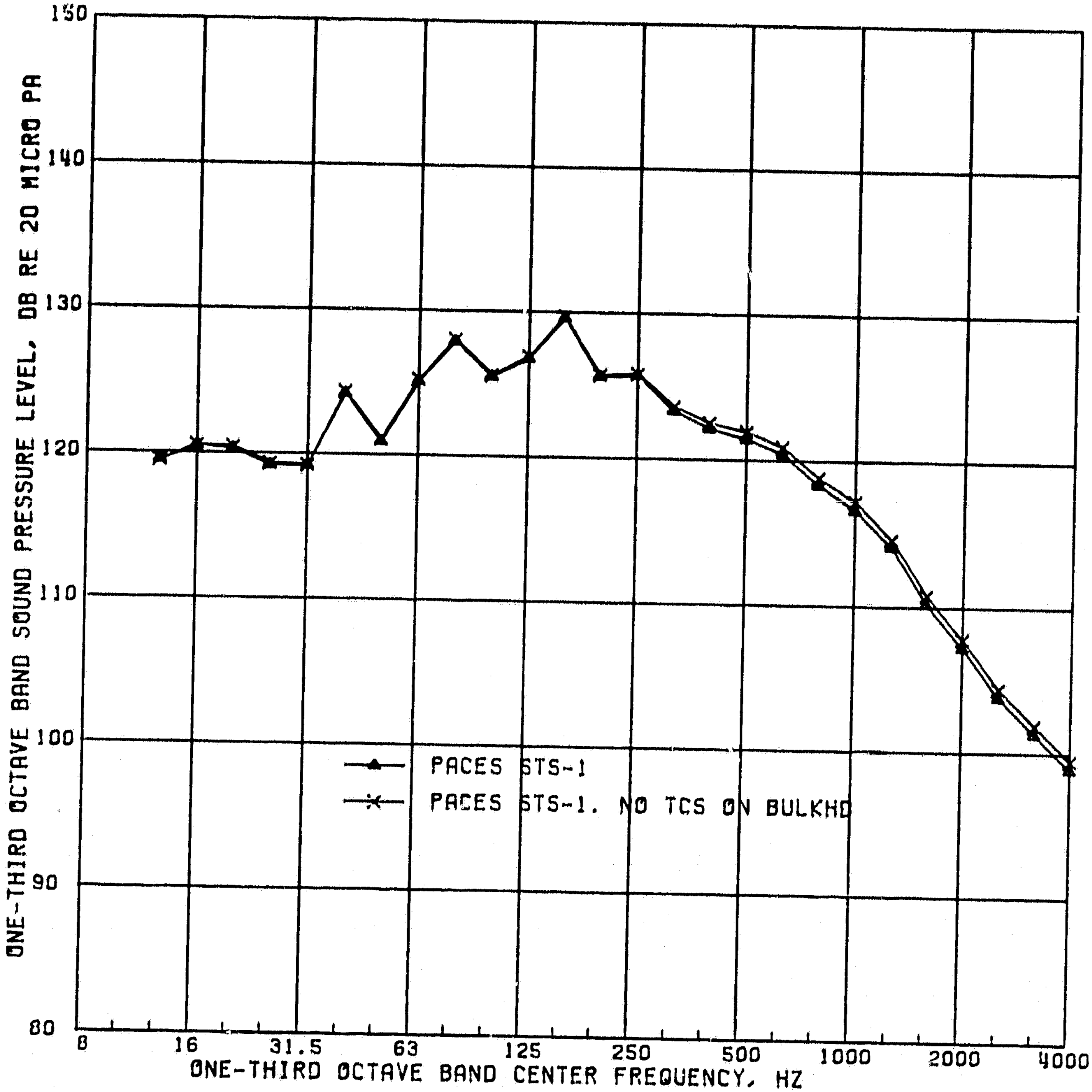

FIGURE 13. PREDICTED SPACE-AVERAGE SOUND PRESSURE LEVELS IN PAYLOAD BAY AT LIFT-OFF

and 15. In Figure 14 the measured levels exclude the correction factor for reflection effects at the bulkheads. This factor is included in the measured levels in Figure 15. The comparison shows that, for frequencies of 125 Hz and below, there is very good agreement between measured and predicted results, particularly if the reflection factors (which have not been validated) are excluded. At higher frequencies (160 - 1250 Hz) the predicted levels exceed the measured values, although the differences are generally less than 5 dB. For frequencies above 1250 Hz, the predicted sound levels are less than corresponding measured values, but the accuracy of the measurements is open to question because of poor signal-to- noise ratios.

6.3 Sensitivity Study

The estimation of space-average sound levels on the exterior of the payload bay involves the interpolation of sound levels between widely spaced transducers. Thus there is the potential for some inaccuracy in the results. These inaccuracies could, in turn, affect the interior sound level predictions. An indication of the magnitude of the effect can be obtained by a simple sensitivity study whereby the exterior sound levels are varied by ± 3 dB for each exterior region in turn. In this case the sidewall and bottom are each considered as single regions, with forward and aft areas being subjected to ± 3 dB changes simultaneously.

The effects of the assumed changes in exterior sound level on the predicted payload bay sound levels are shown in Figures 16 through 19. The ± 3 dB changes to sidewall and bulkhead exterior sound levels have little or no effect on the predicted interior sound levels. In the case of the bottom structure, the effect is significant only in the one-third octave bands centered at frequencies of 63, 80 and 250 Hz. The most important changes

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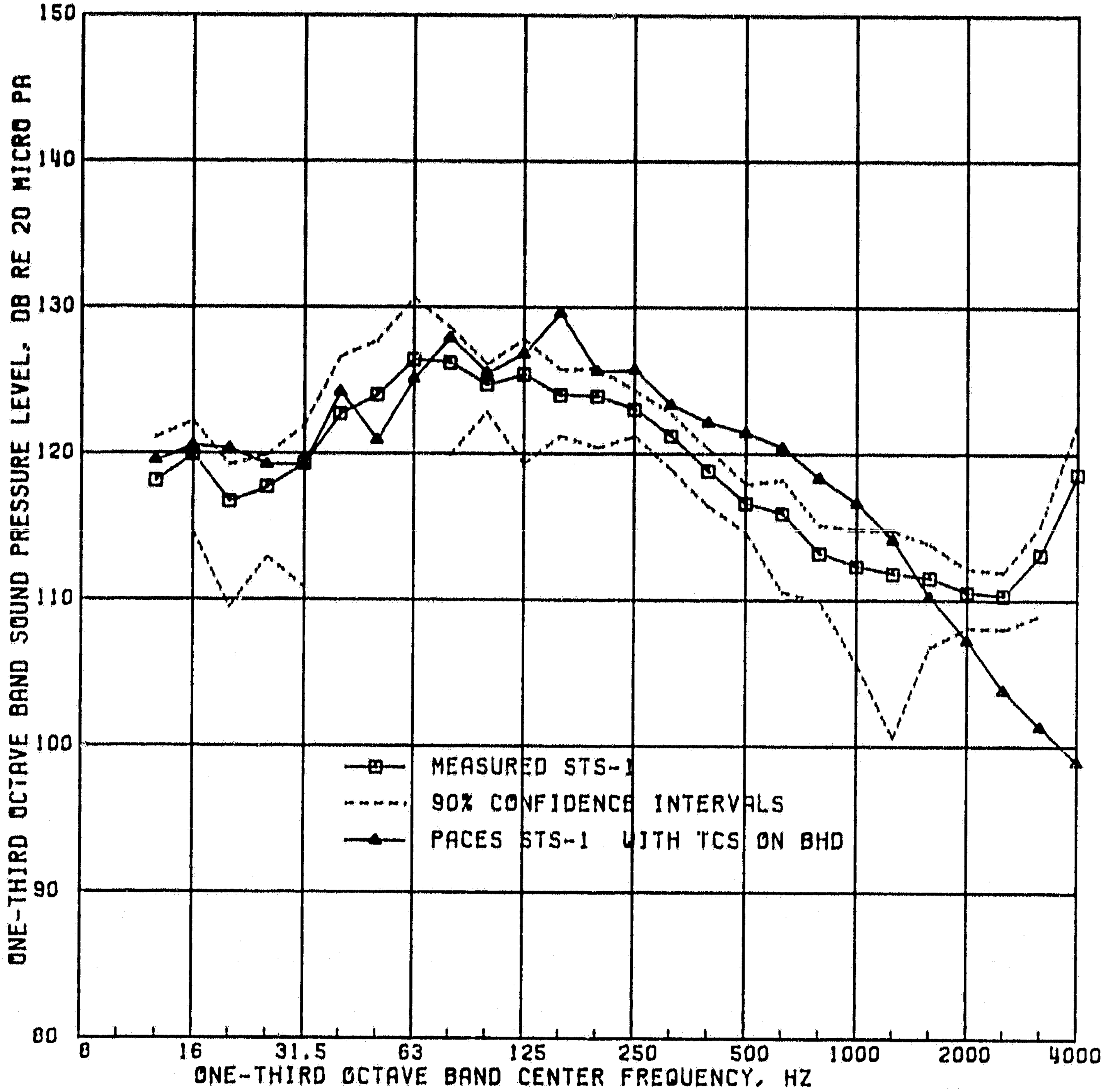

FIGURE 14. COMPARISON OF MEASURED AND PREDICTED SPACE-AVERAGE SOUND PRESSURE LEVELS IN PAYLOAD BAY (REFLECTION EFFECTS EXCLUDED FROM MEASUREMENTS)

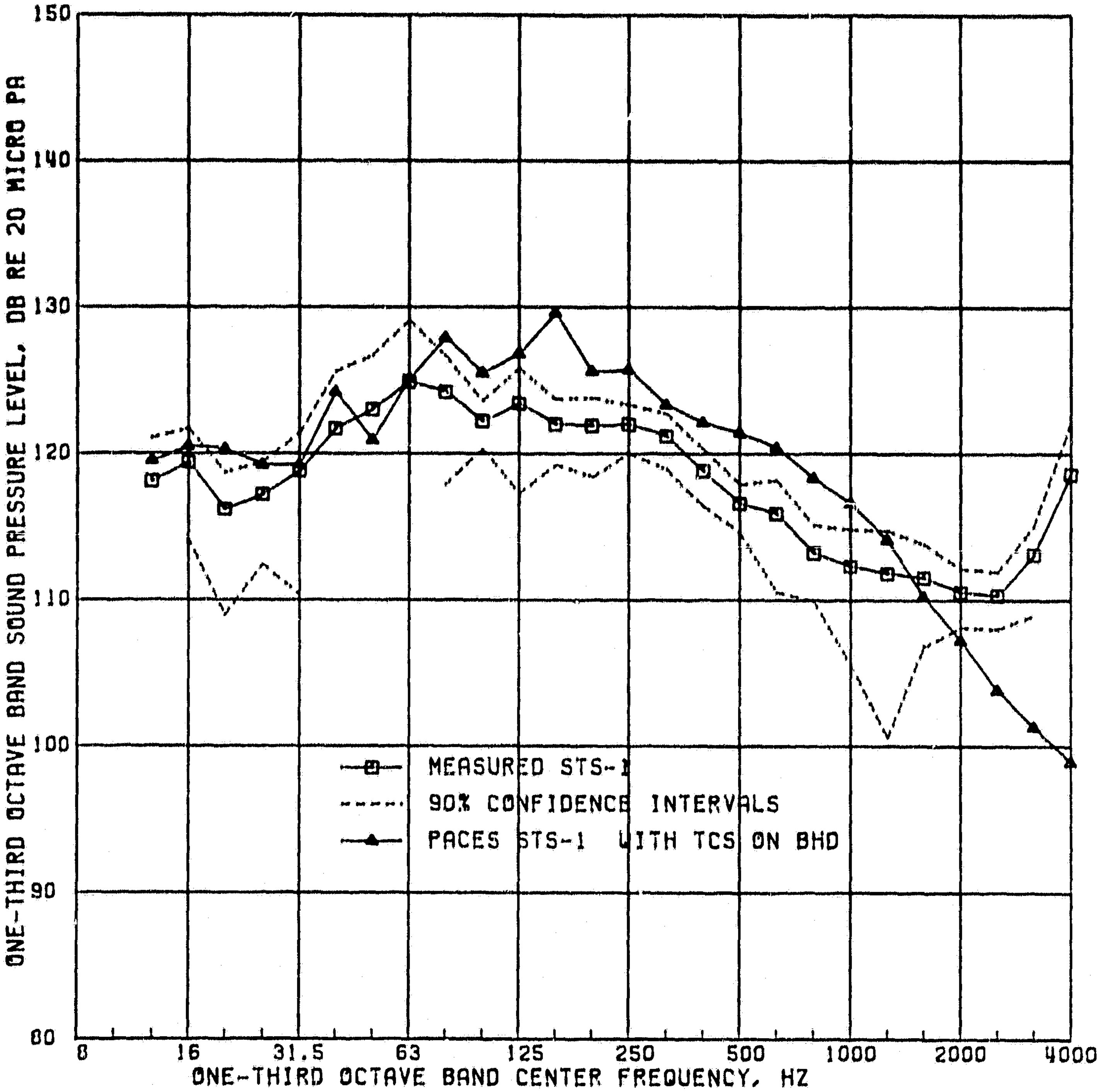

FIGURE 15. COMPARISON OF MEASURED AND PREDICTED SPACE-AVERAGE SOUND PRESSURE LEVELS IN PAYLOAD BAY (REFLECTION EFFECTS INCLUDED IN MEASUREMENTS)

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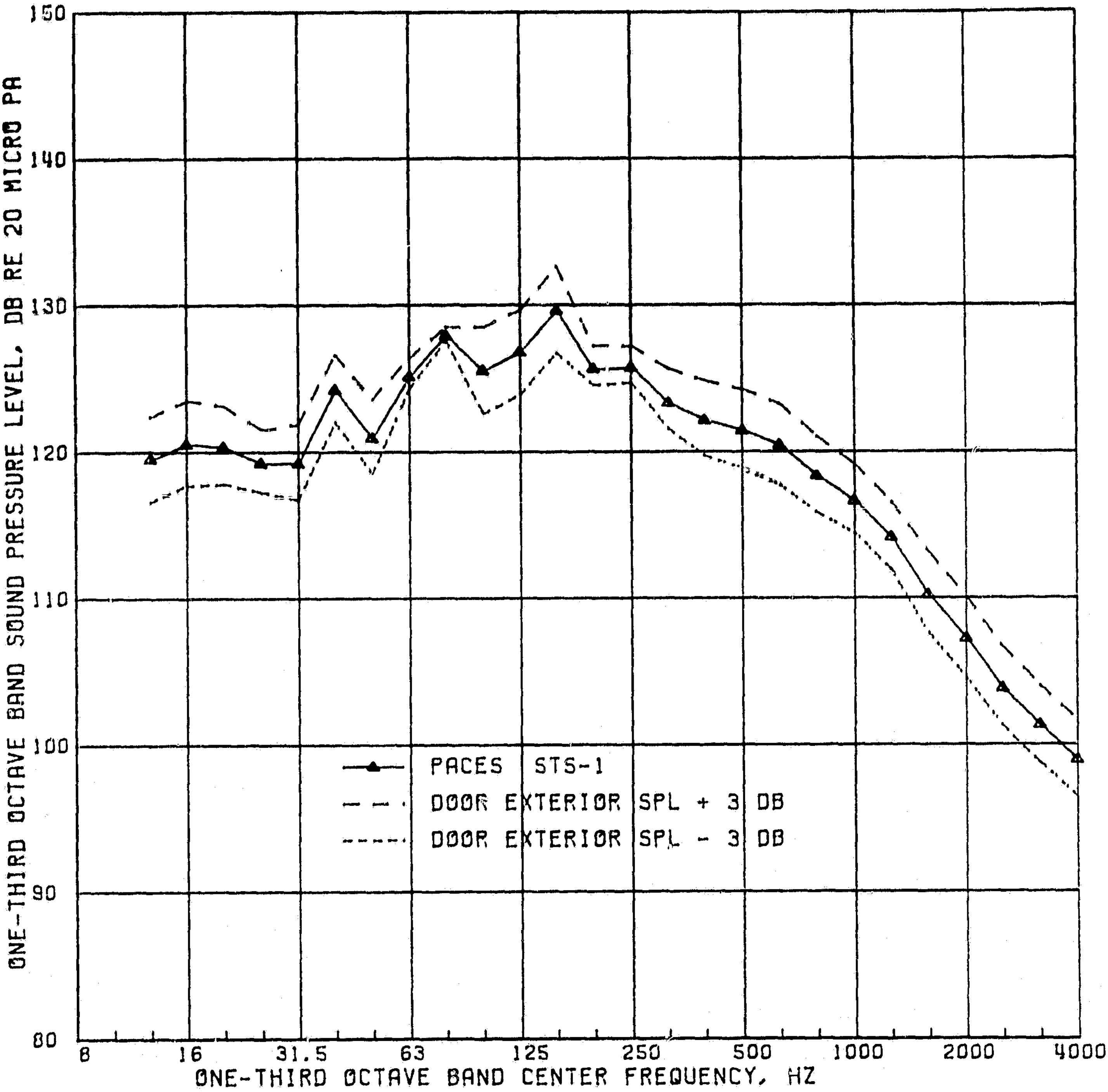

FIGURE 16. EFFECT OF DOOR EXTERIOR SOUND PRESSURE LEVELS ON PREDICTED PAYLOAD BAY SOUND LEVELS

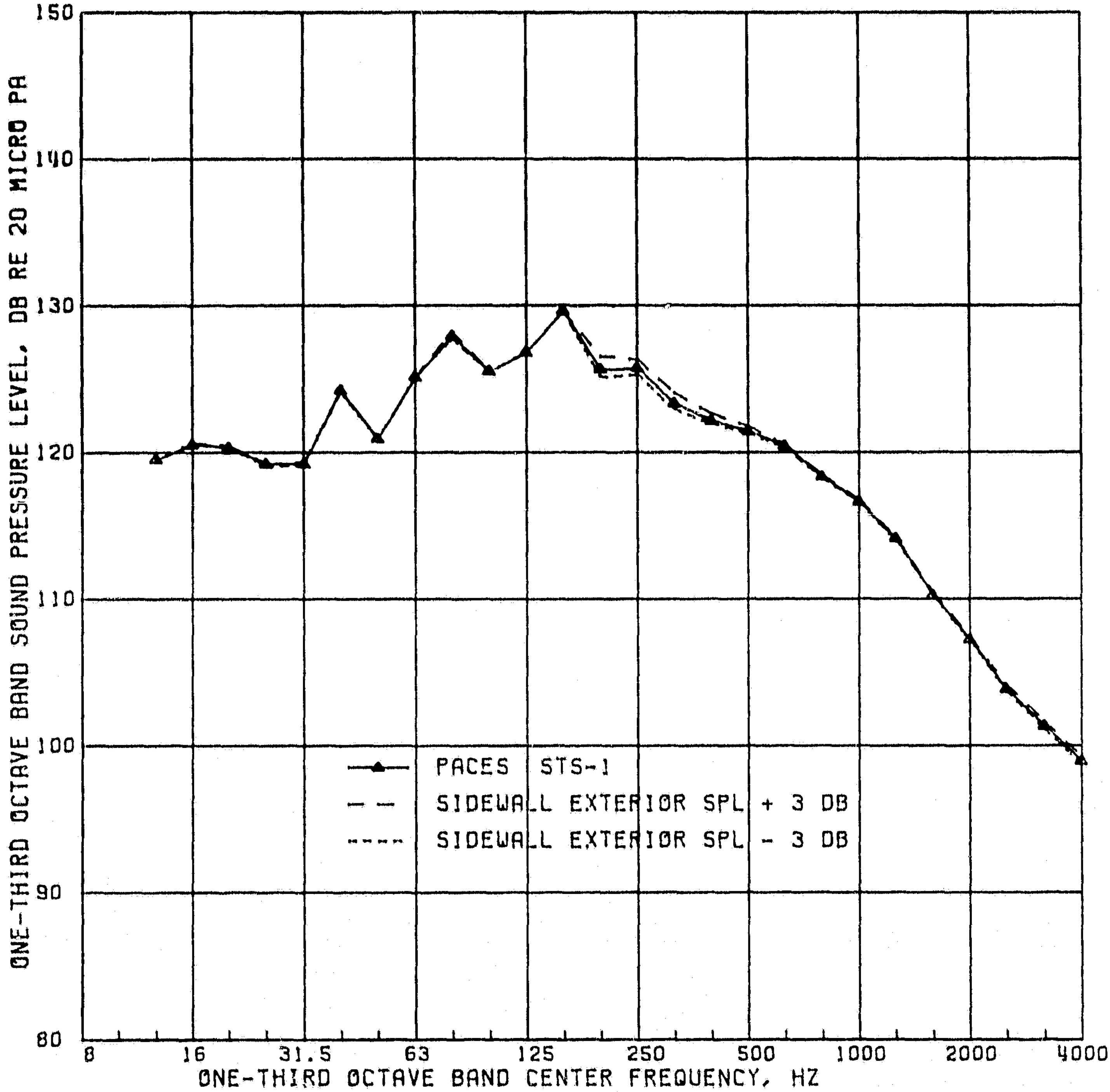

FIGURE 17. EFFECT OF SIDEWALL EXTERIOR SOUND PRESSURE LEVELS ON PREDICTED PAYLOAD BAY SOUND LEVELS

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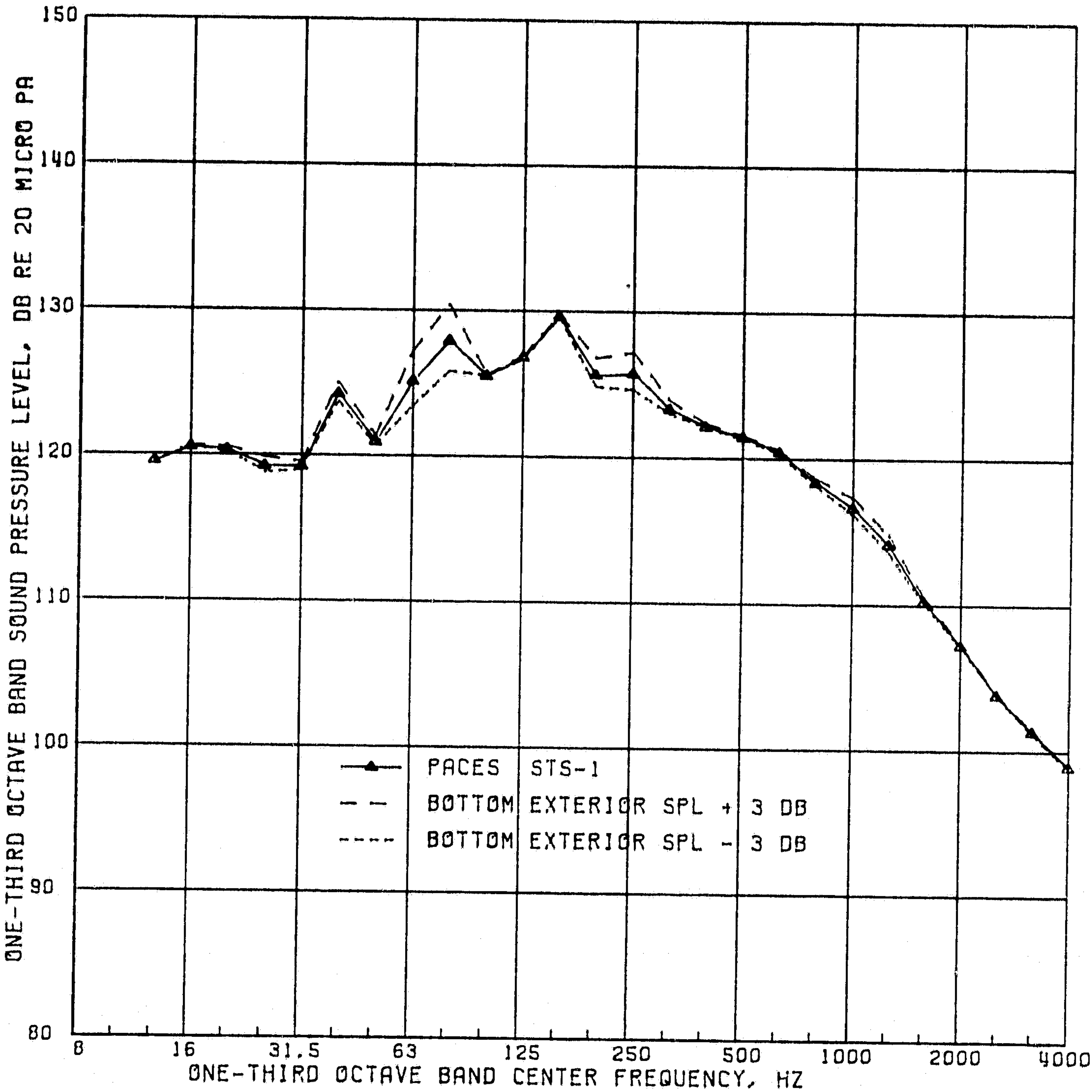

FIGURE 18. EFFECT OF BOTTOM EXTERIOR SOUND PRESSURE LEVELS ON PREDICTED PAYLOAD BAY SOUND LEVELS

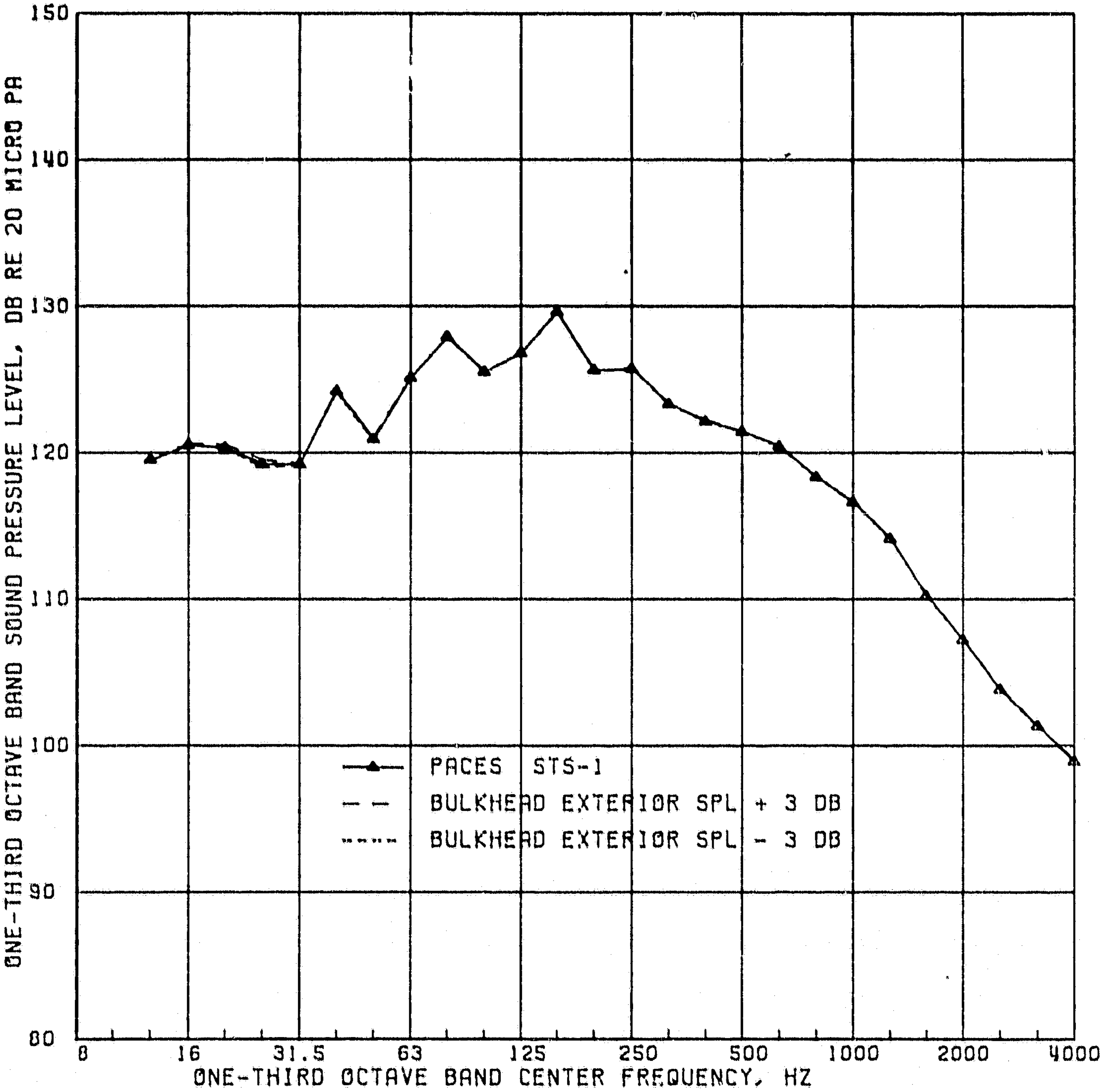

FIGURE 19. EFFECT OF BULKHEAD SOUND PRESSURE LEVELS ON PREDICTED PAYLOAD BAY SOUND LEVELS

of the interior sound level occur when changes of ±3 dB are postulated for the exterior sound field on the payload bay door.

The results of this simple sensitivity study suggest that errors of ±3 dB in the exterior sound levels on the sidewall, bottom structure or aft bulkhead will have only a small effect on the interior sound levels predicted by PACES, because the dominant transmission path is through the payload bay door.

7.0 PAYLOAD BAY VENTS

The analytical model derived in [1] for the acoustic environment in the payload bay assumes that the vents in the sidewall of the bay are closed. However these vents were open for the STS-1 launch. Thus it is necessary to estimate the effect of the acoustic power flow through open vents on the calculated payload bay space-average sound level.

The locations of the vents are shown in Figure 20 and typical vent geometry is shown in Figures 20 and 21. There are eight vents for the payload bay, four on each side of the orbiter. The vents are located at, approximately, X = 765, 905, 995 and 1130, and have a total area of about 0.80 sq. m (8.63 sq. ft.). Each vent consists of a box-like enclosure, the outer face of which is formed by the vent door and TPS tiles. The inner surface consists of a stainless steel filter with 80 x 700 Twilled Double Dutch Weave pleats 8.9 mm (0.38 inch) high at 3 pleats per cm (8 pleats per inch). The vent cavity has an average depth of about 0.36 m (14 inches) and an average length of about 0.53 m (21 inches).

Analysis of the acoustic power flow through the vents considers first transmission through an open slot and then adds the effect of the filter. Two alternative methods have been used to study the acoustic power flow through the open vents. In the first method a vent is modeled as a rectangular piston, in a manner similar to that used in PACES to model connecting openings between payload bay subvolumes around payloads [5]. The power W transmitted by the vent is given by the product of the conductance ξ and the mean square value of the pressure at the surface. Thus

$$W = \frac{\xi}{\rho c} \langle \bar{p}^2 \rangle A \qquad (5)$$

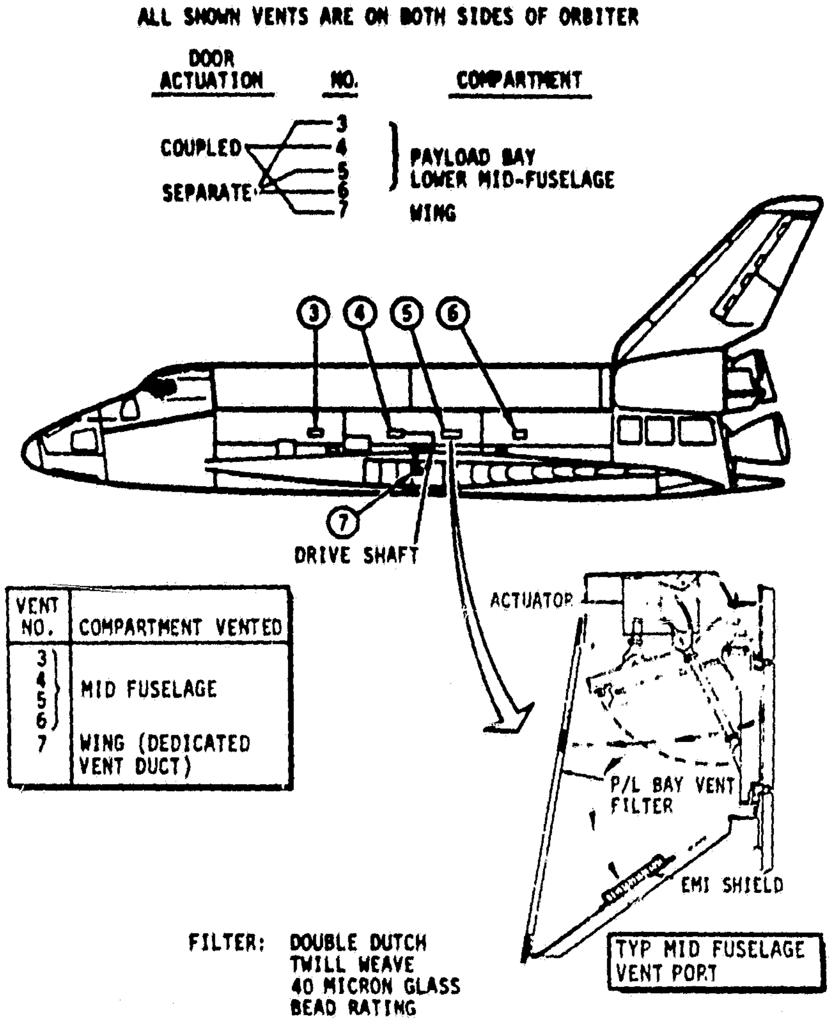

FIGURE 20. PAYLOAD BAY VENT LOCATIONS ON MID-FUSELAGE

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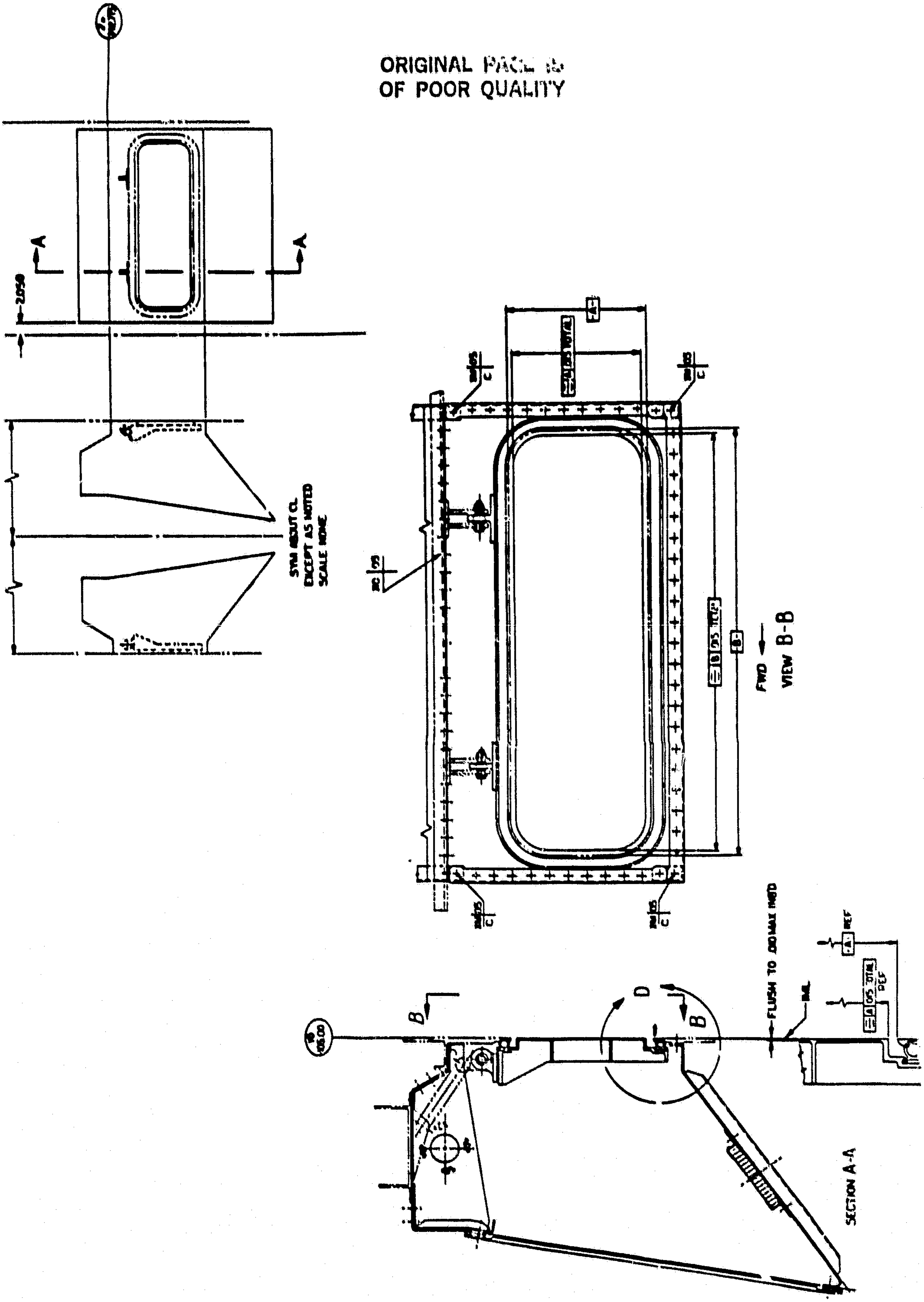

FIGURE 21. TYPICAL VENT GEOMETRY

where A is the area of the vent and the conductance is given by

$$\xi = \frac{\theta}{2(\theta^2+\chi^2)} \qquad (6)$$

with θ, χ being the normalized resistance and reactance, respectively. For typical vent geometries and for the frequency range of interest, $\xi \approx 0.44$ and the equivalent transmission loss is 3.6 dB.

The second approach follows the work of Gomperts and Kihlman [6] for noise transmission through circular and narrow, infinitely long, slit-shaped apertures in walls of finite thickness. The effective wall thickness was defined by the sum of the tile thickness and cavity depth (41.9 cm or 16.5 in). Although the theory predicts the presence of a series of resonances, these are not observed in practice [6]. Furthermore, since the depth of the vent cavity is not uniform any theoretical resonances would be smeared out in frequency, thereby reducing their effect. Consequently, resonance conditions have been neglected in the analysis and only general trends retained. The results indicate that the transmission loss is about 7 dB at low frequencies decreasing to zero at high frequencies.

Noise transmission through a perforated sheet has been studied by Ingard [7] and he shows that the acoustic resistance is usually larger than the reactance for a hole in the sheet. Thus, the transmission coefficient τ for randomly incident sound waves is [7]

$$\tau_r \approx 8\int_0^{\pi/2} \frac{\sin\phi \ \cos\phi}{(\theta\cos\phi + 2)^2}\, d\phi \qquad (7)$$

and for normally incident waves

$$\tau_o \approx \left[1 + \theta/2\right]^{-2} \qquad (8)$$

An estimate of the normalized resistance can be obtained from information [8] regarding the flow characteristics of the filter. The specific (unit area) flow resistance R_f of the filter is given by

$$R_f = \frac{\Delta p}{U} \text{ mks rayls} \tag{9}$$

where the pressure differential p is measured in N/m^2 and the velocity U in m/sec. Then from [8],

$$R_f = 5.6\,U + 41 \text{ mks rayls} \tag{10}$$

For sheet materials the real part of the normal specific acoustic impedance Z_{sn} is approximately equal to the specific flow resistance [9].

Thus

$$\theta = \frac{\mathcal{R}[Z_{sn}]}{\rho c} \approx \frac{R_f}{\rho c} \tag{11}$$

Putting $R_f \approx$ 41 mks rayls, from Eq.(10), gives $\theta \approx 0.1$, and on substitution for θ in Eqs.(7) and (8), $\tau_r \approx 0.94$, $\tau_o \approx 0.91$. The corresponding transmission losses are 0.3 dB and 0.4 dB respectively.

Combining these results, an effective transmission loss of 4 dB has been assumed for all frequencies of interest. This transmission loss is applied to the acoustic power incident on the vent openings, and adjustments estimated for the space-average sound pressure levels in the payload bay. The adjustments and the resulting modified space-average interior sound levels are shown in Table 6. The modified spectrum is a so plotted in Figure 22. It is seen that the differences between the predicted spectra for vents-closed and vents-open conditions are 3 dB or less, except for frequencies of 800 Hz and above. At these high frequencies

Table 6. Estimated Adjustments to Predicted Interior Space-Average Sound Pressure Levels to Allow for Open Vents

Frequency (Hz)	Interior SPL Predicted by PACES (dB)	Adjustments For Open Vents (dB)	Adjusted Interior SPL (dB)
12.5	119.5	2.5	122.0
16	120.5	1.7	122.2
20	120.3	1.7	122.0
25	119.2	2.3	121.5
31.5	119.2	2.2	121.4
40	124.2	1.4	125.6
50	120.9	3.1	124.0
63	125.1	1.3	126.4
80	127.9	1.2	129.1
100	125.5	1.8	127.3
125	126.8	1.5	128.3
160	129.6	0.7	130.3
200	125.6	1.4	127.0
250	125.7	1.6	127.3
315	123.3	1.9	125.2
400	122.1	2.6	124.7
500	121.4	2.2	123.6
630	120.4	2.5	122.9
800	118.3	3.2	121.5
1000	116.6	3.6	120.2
1250	114.1	5.2	119.3
1600	110.2	7.5	117.7
2000	107.2	9.7	116.9
2500	103.8	11.6	115.4
3150	101.3	13.8	115.1
4000	98.9	16.6	115.5

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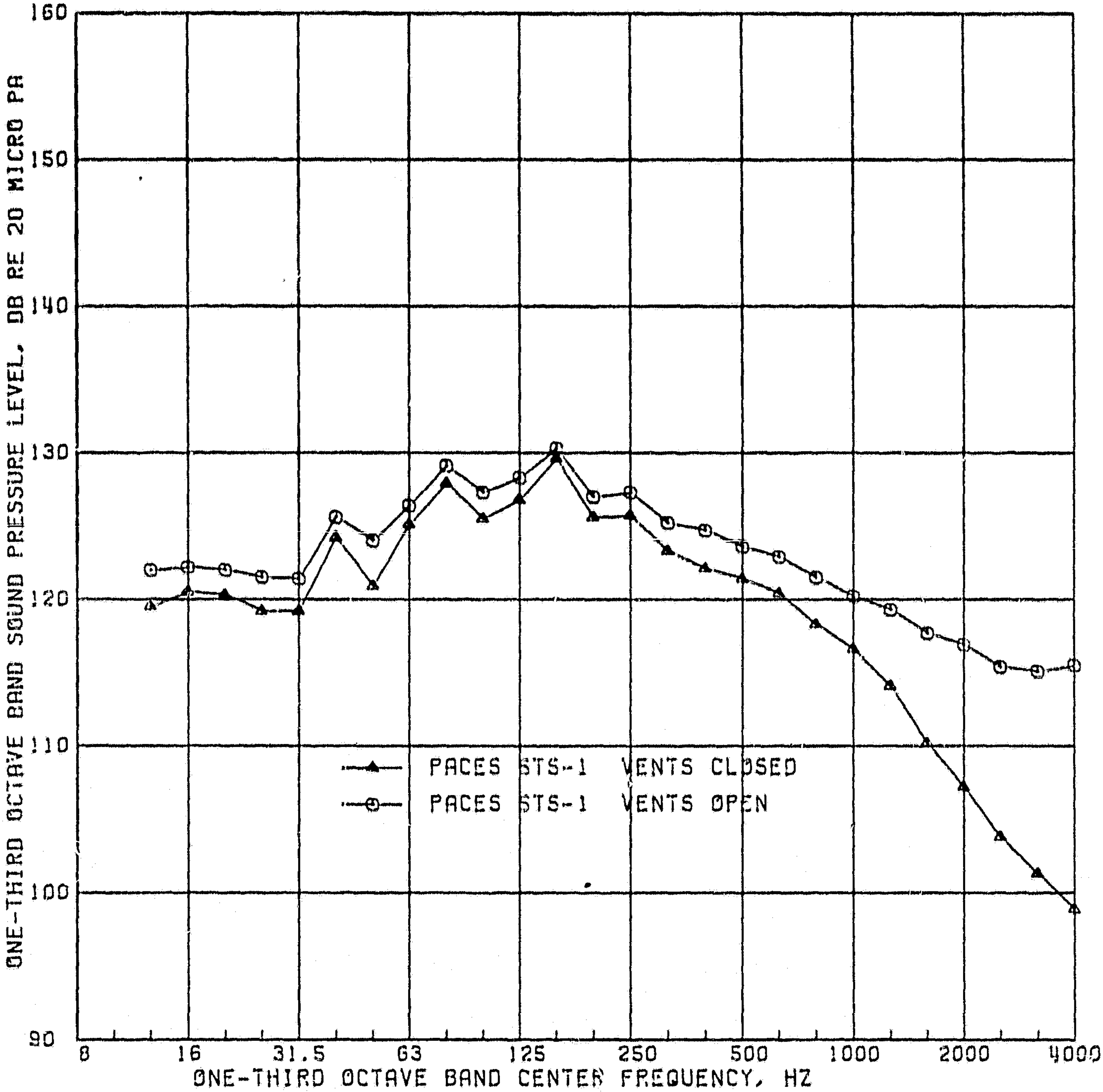

FIGURE 22. ESTIMATED EFFECT OF VENTS ON PREDICTED PAYLOAD BAY SPACE-AVERAGE SOUND PRESSURE LEVELS

the transmission loss provided by the structure is large, with the result that the acoustic power flow through the vents becomes a dominant factor.

The adjustments have to be treated as provisional in the light of the many assumptions made in the calculation procedures. It is anticipated that data from subsequent launches will improve the understanding of the role played by the vents. The results in Table 6 do show, however, that the accuracy of the estimates for the exterior sound pressure levels on the sidewall is now very important because of the direct influence on the calculated acoustic power transmission through the open vents. This fact should be borne in mind in the analysis of data from future launches.

8.0 CONCLUSIONS

A limited amount of acoustic data measured during STS-1 lift-off has provided the basis for a comparison between measured payload bay sound levels and corresponding predicted levels calculated using the PACES computer program. The comparison shows good agreement between measurements and predictions in the frequency range 12.5 to 125 Hz, but the predicted levels are 2 to 5 dB higher than measured values for frequencies 125 to 1250 Hz. However several factors should be noted:

(a) Payload bay sound levels were measured at only four locations, three of which were close to large reflecting surfaces. It was not possible to establish 90% confidence limits throughout the frequency range of interest.

(b) A simple analytical model has been proposed to describe the reflection effects but the accuracy of the model cannot be determined. The agreement between measurements and predictions is better when the reflection effects are omitted than it is when corrections are included for the reflections.

(c) Because of the small number of locations used to measure the exterior sound field it was necessary to develop interpolation procedures to estimate space-average sound levels on the exterior of the payload bay. This introduces some potential for error. However, a simple sensitivity analysis suggests that the errors (assuming that they are not greater than ± 3 dB) will not be significant except for the payload bay door.

(d) The analytical model associated with PACES assumes that the payload bay vents are closed at lift-off so that there are no acoustic leaks. For STS-1 launch, these vents were open.

Because of these uncertainties regarding the data, no modifications to the analytical model or PACES are considered at this stage. Rather, it is proposed that the need for such modifications be considered only after data from other launches have been analyzed. In particular, the STS-2 launch should provide measurements for many more locations in the payload bay, thereby improving the accuracy of the measured space-average sound levels in the bay. The additional data may also provide greater insight into the noise transmission path through the open vents.

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